U.S. DEPARTMENT OF THE INTERIOR
BUREAU OF LAND MANAGEMENT

BLM

National Training Center

Course Number 1730-25

Aquatic Habitat Restoration and Enhancement

Aquatic Restoration and Enhancement; Thoughts About Project Monitoring.

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A creek, given its visual complexity, is a surprisingly simple construction.

Two nouns: Water and Land. One Verb: Gravity.

David James Duncan
My Story as Told by Water

Task 1: Identify three reasons why monitoring projects fail.

- Think about past aquatic restoration monitoring projects you have been involved with and why they may have failed.
- If you haven't been involved in restoration projects, think of ways monitoring efforts may fail.
- Work with someone if you want, keep answers short (one paragraph).

Why Monitoring Programs Fail?

- Design- Stats/Sampling
  - Inherent in the study plans.
  - No amount of conscientious implementation would save them.
- Procedural
  - Derail even well designed programs

Why Monitoring Programs Fail?

Non-Ideal Field Workers (P)	37%
Method Can't Measure (D)	30%
Data Not In Time (P)	27%
Study To Short (D)	27%
Collateral Info Missing (P)	20%
Cryptic Technology (P)	17%
Inadequate Problem Analysis (D)	17%
Misunderstanding of System (D)	13%
Weak Statistical Design (D)	13%

Almost As Many Projects Fail Because of Procedural Problems as They Do Design Problems

This means you need to focus as much on logistical design as statistical design.

Design Concerns

- Good objective statement – addresses the question, measurable, and repeatable. Introduction Problems
- Statistics. The Numbers. Methods Problems.

Methods Can't Measure.

- Does the character measured and/or the way it is measured get at objectives?
  - How and where should the attribute be measured.
  - Which attributes should be measured.

Study to short

- Not to short because of money but because of plans.
  - Graduate Student Time-Frame
- Not to short because of money but because of conditions.
  - Sample size estimates could be based on past condition that change, i.e. cycle changes from drought to above-average precipitation.

Inadequate Problem Analysis. Misunderstanding of Problem.

- Collect data that is irrelevant.
  - Is the variable affected by the issue being monitored
  - Have all the variables affected by the issue of interest been.
- Collected information would not answer question in time to be meaningful.
  - Information not available at time study began.

Finally – Weak Statistical Design.

- I often get involved at this point. Common question suggesting weak statistical design is, "How do I analyze my data?"
- There are always ways to address weak statistical designs but they always undermine the strength of your conclusions.
  - Representative, arbitrary, I made the assumption,...

Do You Really Need Statistics?

- Are you interested in specific results or are you interested in general results?
- Do you have a specific question or general question?
- Are you interested in the error associated with the measurement?

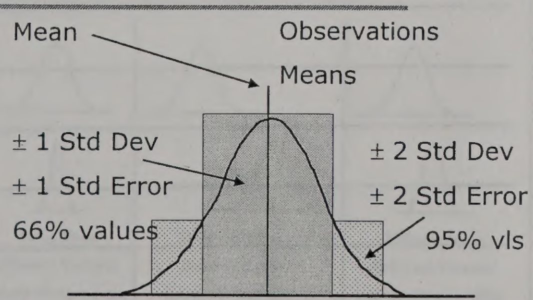
If you need statistics what do you need to focus on?

- Variance → How much difference between streams, observers, and through time.
- Difference → What kind of changes do you need for statistical or biological significant changes.
- Attribute → Which attribute should you measure? How does it change? How easy is it to measure

Standard Statistical Terms

Mean	$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n}$	Central Tendency
Standard Deviation	$s = \sqrt{\left(\frac{\sum_{i=1}^{n} (\bar{x} - x_i)^2}{n-1}\right)}$	Dispersion
Standard Error	$se = (s/\sqrt{n})$	Sample Dispersion

What is a distribution?



What is a Statistical Test?

Null Hypothesis

$$H_0; \mu_{group1} = \mu_{group2}$$

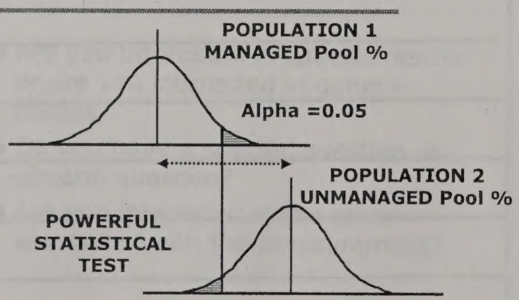
Alternative Hypothesis

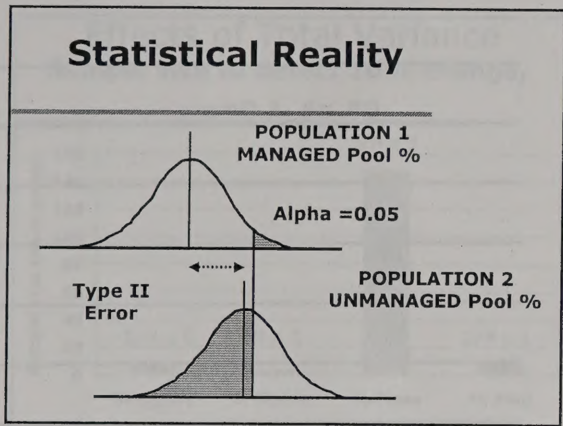
$$H_A; \mu_{group1} \neq \mu_{group2}$$

Type I vs. Type II Errors for testing mean differences

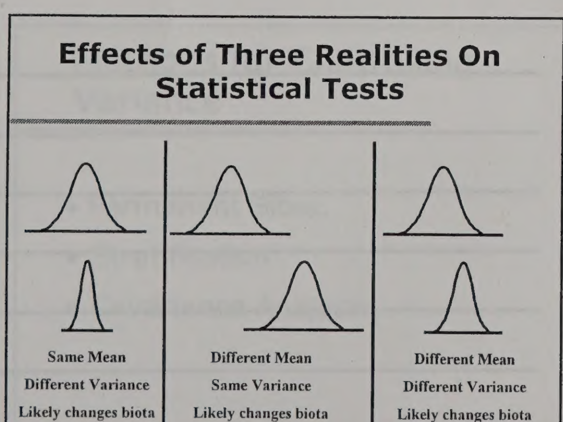
		Hypothesis is really True	Hypothesis is really False
Decision based on test of significance	Accept	No Error	Type II Error
	Reject	Type I Error	No Error

Statistical Ideal





Statistics Exercise



Which Attribute to choose?

- Fine Sediment
- Pool Percentage
- Bank Stability

Rank from 1 (best) to 3 (worst) attribute. Restoration at the watershed scale.

1) How do you measure? 2) How does management affect it? 3) Difference among streams? 4) Difference among observers?, and 5) Is it related to the biological systems?

Sources of Variation Affecting Monitoring Results

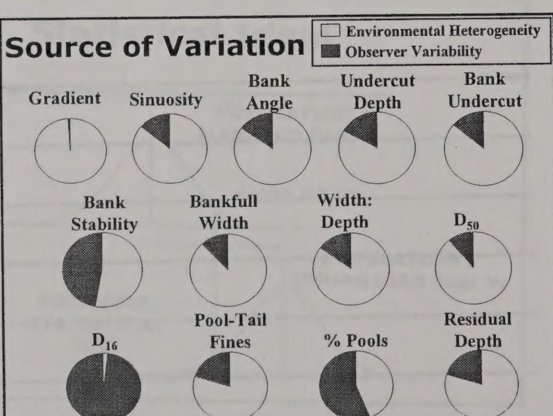
- Measurement Error
- Surveyor Error

Observer Variation (Noise)

- Site Variation (Signal)
  - Surveyor by Site (Noise)
- Year Variation

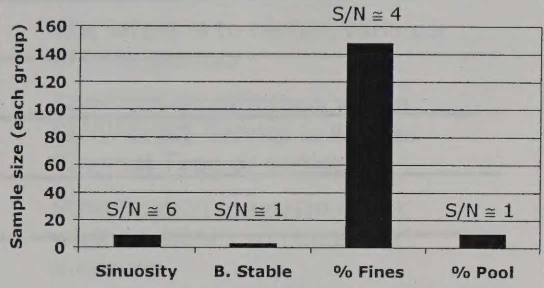
Concordant
Discordant

Source of Variation

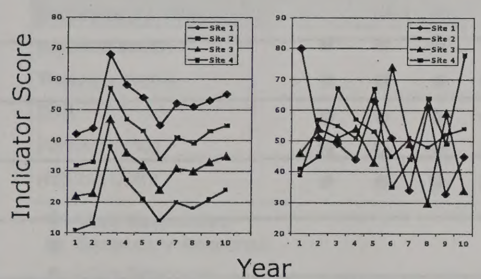


Effects of Total Variance

Sample size to detect 20% change, α=0.1, β=.80



Concordant vs. Discordant

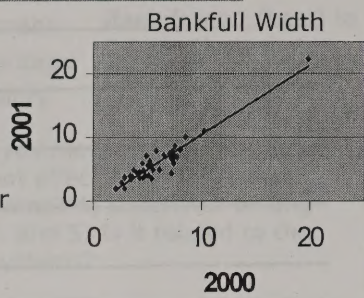


Methods for Controlling Variance

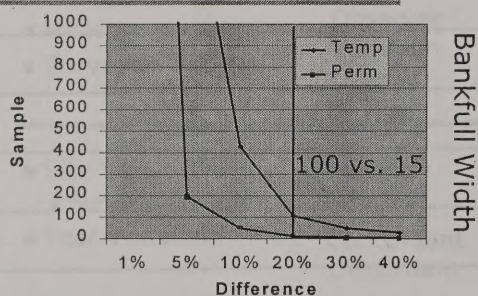
- Permanent Sites.
- Stratification
- Covariance Analysis

Permanent Sites

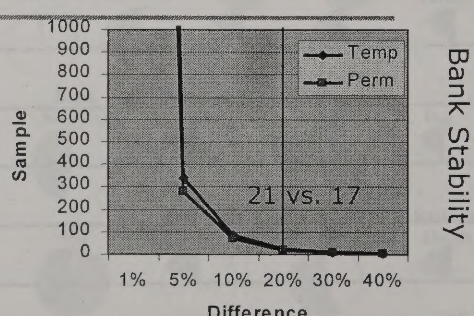
Use when there is a high correlation between year-to-year results.



Sample Size Permanent vs. Temporary



Sample Size Permanent vs. Temporary



Stratification --

The intent is to reduce variance among groups.

Standard stratification within BLM/Forest Service is Rosgen Channel Type or geology.

Stratification may also affect what variable you choose to measure.

Sensitivity to Change
- Adding Sediment <2 mm

Response Variable	C	SP	PB	PR
Bankfull Width	●	●	●	■
Thalweg Profile	●	■	●	◆
D50	●	●	◆	◆
Percent Fines	■	■	◆	◆
Habitat Units	●	●	●	■

◆ Very Responsive
■ Secondary Response
● Little Response

Montgomery and MacDonald 2002

Sensitivity to Change
- Increasing Flows

Response Variable	C	SP	PB	PR
Bankfull Width	■	■	◆	◆
Thalweg Profile	●	■	●	◆
D50	●	●	◆	◆
Percent Fines	■	■	◆	◆
Habitat Units	●	●	●	●

◆ Very Responsive
■ Secondary Response
● Little Response

Montgomery and MacDonald 2002

Theoretical Rates of Change for Low Gradient Reaches

Rate of Change

Fast → Slow

Attribute Character	Channel Character	Geomorphic Character
Substrate Size	Bank Stability	Sinuosity
Large Wood Numbers	Habitat Composition	Gradient
Biota numbers	Residual Depth	

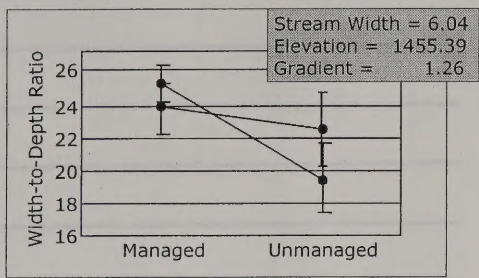
Analysis of Covariance (ANCOVA)

The use of ANCOVA removes variability in an experimental unit that could not be controlled for in the survey design. This is a common occurrence in studies on the effects of land management. For example, managed watersheds can differ from unmanaged watersheds in their gradient, basin area, and elevation.

Characteristics of Minimally Managed and Unmanaged Watersheds Within the Upper Columbia River Basin

Variable	Managed Mean (STD)	Unmanaged Mean (STD)	p-value Mean (STD)
Elevation	4576.70 (1333.4)	5443.99 (1384.9)	<0.001 (0.679)
Gradient	1.27 (0.702)	1.20 (0.718)	0.526 (0.798)
Sinuosity	1.34 (0.314)	1.42 (0.384)	0.106 (0.370)
Area	39.87 (28.57)	31.32 (25.69)	0.304 (0.316)
Stream width	5.67 (2.943)	6.69 (4.088)	0.004 (0.001)
Stream Density	1.58 (0.654)	1.57 (0.936)	0.871 (<0.001)
Road Density	1.60 (1.109)	0.15 (0.392)	<0.001 (<0.001)
% Federal	95.40 (7.74)	99.84 (0.665)	<0.001 (<0.001)
Precipitation	810.26 (302.6)	1013.63 (284.3)	<0.001 (0.561)
	n=203	n=67	

So what does ANCOVA buy you?



Conclusions

- Need to be worried about both procedural and design concerns.
  - Projects fail about equally for both reasons.
  - Both reasons for failure are taken care of up front. Think long and hard about your monitoring project before you implement it.

Conclusions

- Need to understand what aspects of your survey design is likely to have variation.
  - Can pick repeatable attributes that are likely to be change.
  - Understand high variability leads to large sample sizes.
  - Biological vs. Statistical Significance.

Conclusions

- Need to understand you options for survey design.
  - Do you really need statistics?
  - How do you alter design to reduce variability.
  - How do you alter analysis to reduce variability.

Discussions?

Agenda & Roster

Course Schedule:
Aquatic Habitat Restoration and Enhancement

Monday August 5,
Assessment of Fish Needs
- Species of Interest (sport fish, sensitive species, guilds, communities, etc.)
- Habitat requirements (life histories, population status, interspecific interactions, requirements by life stage, periodicity charts, etc.)
- Habitat information (temporal considerations; macro-, meso-, micro-habitat scales; passage issues; watershed-down approach)
- Assimilation of information (reference conditions, tools, etc.)

Tuesday August 6,
Restoration of Flow Regimes
- Quantitative, measurable goals
- Minimum flows, dynamic conditions, mimicking the natural hydrograph
- Overview of methods (historical methods, transect methods, habitat simulation, natural variability)
- Developing recommendations (exercises using the various methods and their results)

Wednesday August 7,
Passage & Connectivity
- Connecting the river system
- Barrier analysis
- Channel modifications, fishway designs, culvert analysis and design
- Field trip and class exercises

Thursday August 8,
Structural Modifications
- Pros and cons (past performance, passive vs active approaches)
- Planning and implementation (a 12-step process)
- Tools of the trade and design criteria (weirs, berms, constrictors, deflectors, substrate modifications, bank treatments, habitat complexity)
- Evaluating performance (risk, hydraulic relations, physical models, habitat models)

Friday August 9,
Monitoring, Evaluation, and Reporting
- Monitoring Statistics

Participant List
Aquatic Habitat Restoration and Enhancement
Course 1730-25
Albuquerque, New Mexico
August 5-9, 2002

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Day 1
Fish Needs

BLM TRAINING COURSE No. 7000-12
AQUATIC HABITAT RESTORATION & ENHANCEMENT
August 5 - 9, 2002
Albuquerque, NM

DAY ONE: Assessment of Fish Needs - What's the Problem?

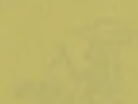
- Introduction & Overview - What are we doing here? (30 minutes)
  - ✓Course goal and objectives
  - ✓Schedule for the week
  - ✓Focus areas
  - ✓Definitions
- Identifying your target species - Who do we want to manage for? (30 minutes)
  - ✓Species management
  - ✓Community approach to restoration
  - ✓Discussion - Participant's species of interest
- Developing information for your target species - What do we need to know? (1 hour)
  - ✓Population status, past & present
  - ✓Age, growth & condition
  - ✓Reproductive strategy
  - ✓Food requirements
  - ✓Predator-prey relationships
  - ✓Habitat requirements by life stage
  - ✓In-class Problem #1 - Developing periodicity charts & habitat matrices
- Developing your habitat information - Where and when is it available? (2 hours)
  - ✓Watershed-habitat relations
  - ✓Variability is a way of life! Spatial & temporal
  - ✓Spatial & temporal considerations - Hierarchical organization of a stream system
    - ☺Longitudinal zonation
    - ☺Latitudinal zonation
    - ☺Macrohabitat - hydrology, WQ, temperature, morphology, riparian vegetation
    - ☺Mesohabitat - riffles, pools, runs, glides....
    - ☺Microhabitat - depth, velocity, substrate, cover...
    - ☺Additional considerations - barriers, ice dynamics, flow variability.....
    - ☺In-class Problem #2 - Identifying instream habitat features and processes
  - ✓Morning Wrap-up - Designing your study from the watershed down (Case study)
- **Lunch Break**
- **AFTERNOON WORKSHOP** - The search for potential limiting factors! (4 hours)
  - ✓The reference stream approach (1 hour)
    - ☺Background, purpose, approaches....
    - ☺In-class Problem #3 - How close is close enough? Clark Fork River case study
  - ✓Temperature and habitat as limiting factors (3 hours)
    - ☺Stream Segment Temperature model - Software demo and In-class Problem #4
    - ☺HEP/HSI - Model applications & In-class Problem #5
  - ✓Discussion & wrap-up for Day 0ne.

BLM Training Course

Aquatic Habitat Restoration and Enhancement

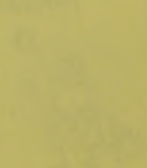
Introductions

Tom Wesche
Lora Wesche
Jim Fogg
Brett Roper
Participants



Goal

Enhance your confidence
and
abilities in
aquatic habitat restoration



BLM Training Course

Aquatic Habitat Restoration and Enhancement

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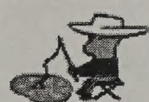
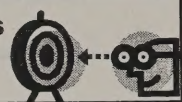


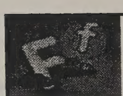
Goal

Enhance your confidence and abilities in aquatic habitat restoration

Objectives

- Assess habitat needs
- Identify potential limiting factors
- Plan and design restoration/enhancement measures
- Monitor habitat gains



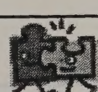


Overview

Habitat Restoration Analysis and Design

Day 1 Assessment of Fish Needs
Day 2 The Basic Ingredient – Water!
Day 3 Fish Passage and Field Trip
Day 4 Structural Modifications
Day 5 Monitoring

Day 1



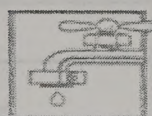
Assessment of Fish Needs

- Identifying "target" species
- Developing information for "target" species
- Developing habitat information
- Putting it all together
- Developing quantitative, measurable restoration goals

Day 2

The Basic Ingredient – WATER

- **Flow as a potential limiting factor**
- **History of instream flow**
- **Overview of instream flow methods**
- **Developing instream flow recommendations**



Day 3

FISH PASSAGE

- **Re-connecting the river system**
- **Barrier analysis**
- **Fish passage solutions**
- **Field trip**

Day 4

Structural Habitat Management

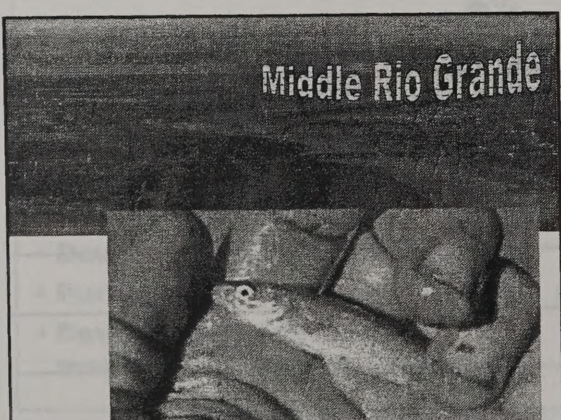
- **Pro's and Con's**
- **Planning and implementation**
- **Tools of the trade**
- **Workshop – Evaluating design**

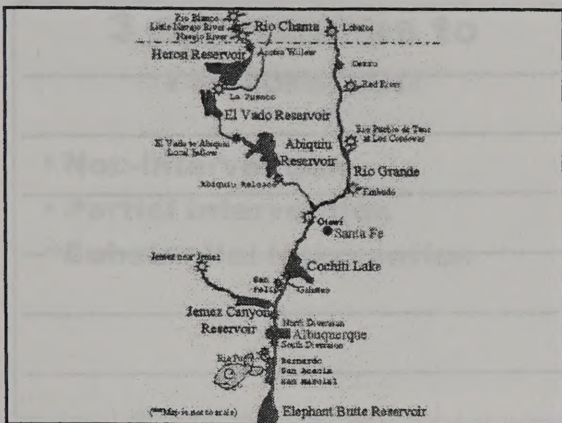
Day 5

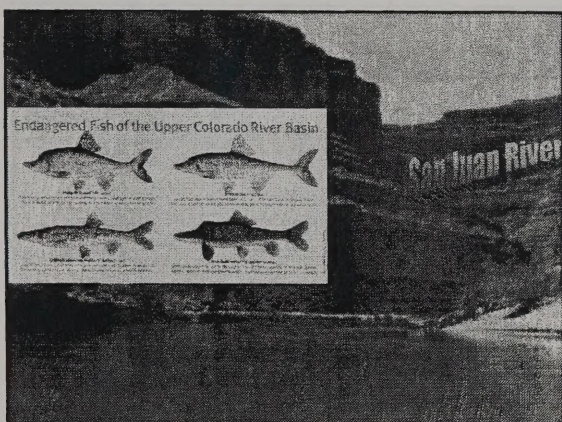
- **Monitoring**
  - Dr. Brett Roper

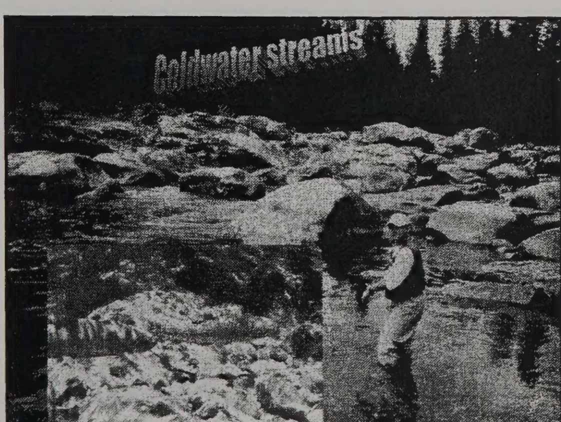
Focus Areas

- **Middle Rio Grande**
- **San Juan River**
- **Montane, coldwater streams**



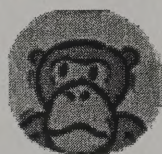

Rio Blanco
Little Navajo River
Rio Chama
Heron Reservoir
Red River
El Vado Reservoir
Abiquiu
Reservoir
Rio Grande
Embudo
Santa Fe
Cochiti Lake
Galisteo
Jemez Canyon
Reservoir
North Diversion
Albuquerque
South Diversion
Elephant Butte Reservoir

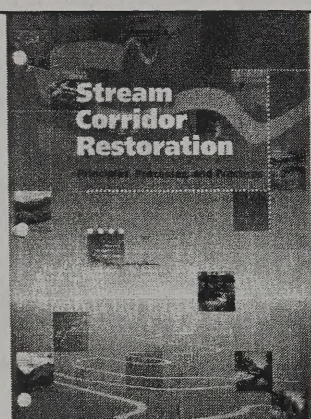

Endangered Fish of the Upper Colorado River Basin
San Juan River


Coldwater streams

Definitions

- Restoration
- Rehabilitation
- Reclamation





"Human activity has profoundly affected rivers and streams in all parts of the world, to such an extent that it is now extremely difficult to find any stream which has not been in some way altered, and probably quite impossible to find any such river."

- H.B.N Hynes 1970

FISRWG 1998
(Handout)

Restoration

"reestablishment of ecosystem structure and function"

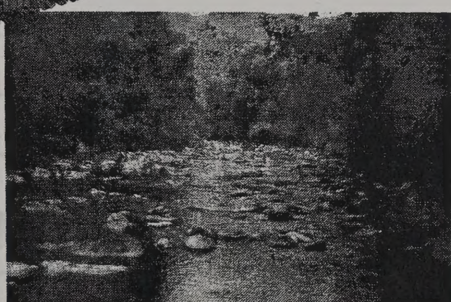
- Return to pre-disturbance conditions
- Recognize that ecosystems are naturally dynamic
- Not always possible to re-create exactly
- Include measures to restore dynamic equilibrium
- First step....halt the disturbance activities

FISRWG 1998

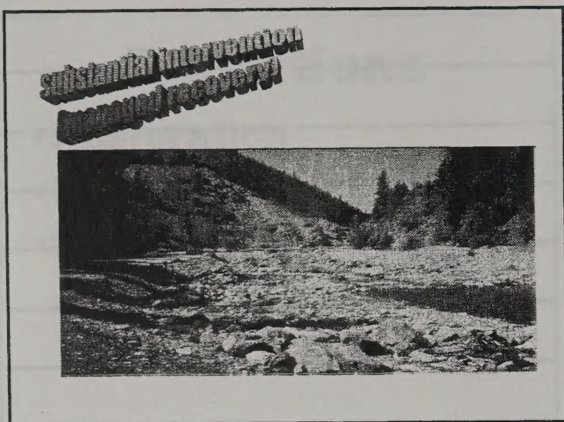
3 approaches to restoration

- Non-intervention
- Partial intervention
- Substantial intervention

Non-intervention (undisturbed recovery)



Partial intervention (assisted recovery)



Rehabilitation
"making land useful again after disturbance"

- **Doesn't** reestablish pre-disturbance conditions
- **Does** reestablish geologic and hydrologic stability
- Can the Middle Rio Grande be rehabilitated?

FISRWG, 1998

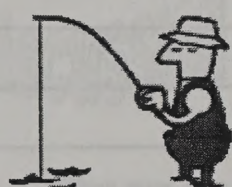
Reclamation

"activities changing biophysical capacity of ecosystem"

- Historically implied adapting natural resources to human purposes
- Can we do "reclamation" work on a stream?

FISRWG 1998

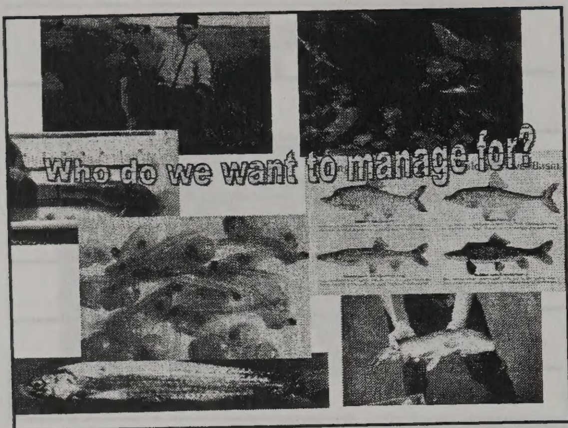
The Bottom Line



Don't get caught up in semantics!

Identifying your "target" species

- **Sport fisheries**
- **Endangered species**
- **Non-natives**
- **Concept of guilds**
- **Community approach**

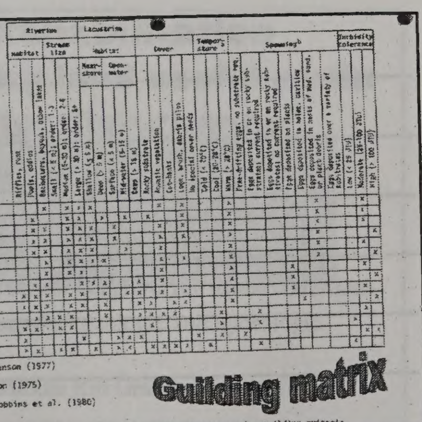


Guilds

"an ecological group distinguished by a special mode of life"

- Groupings based on similar habitat requirements
- Evaluation species selected to represent each guild
- Can simplify analysis
- Overcomes data gaps

(Handout)



Community approach to restoration

- "ecosystem management"
- Not species specific
- Focus on hydrologic, chemical and geomorphic functions
- Often involves total corridor/channel reconstruction
- Assumes biota will respond
- Often similar to species management

Discussion

Who are we managing for?

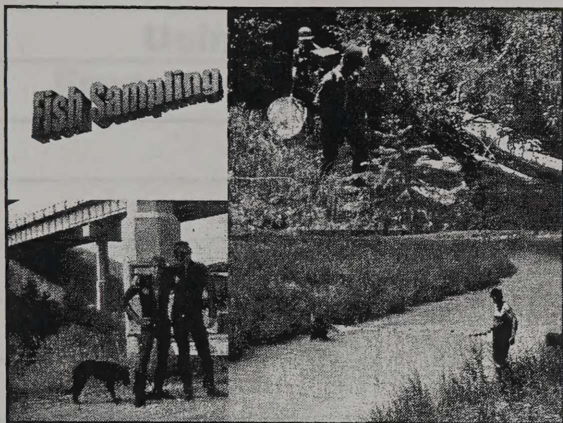
Developing life history information for your "target" species

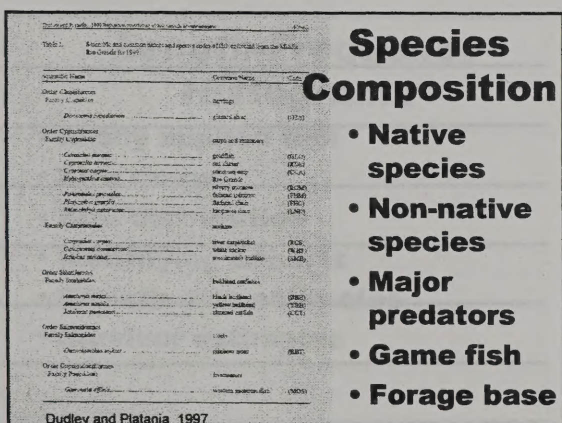
- **Population status**
- **Age, growth and condition**
- **Reproductive strategy**
- **Predators, competitors, and prey**
- **Habitat requirements by life stage**
- **Developing periodicity charts**

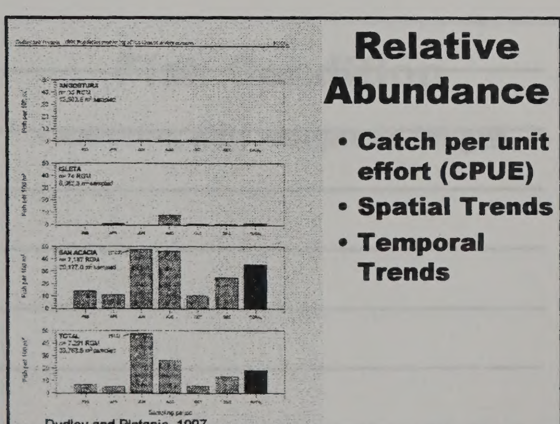
"Remember, what we need to know and what we'd like to know may differ!"

Population Status – past and present

Locating historical records may not be easy


Fish Sampling


Species Composition
• Native species
• Non-native species
• Major predators
• Game fish
• Forage base
Dudley and Platania 1997


Relative Abundance
• Catch per unit effort (CPUE)
• Spatial Trends
• Temporal Trends
Dudley and Platania 1997

Population Estimates

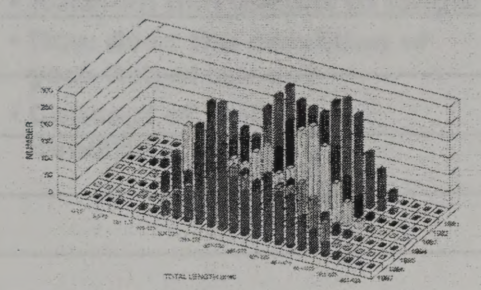
- Increased emphasis due to ESA recovery goals
- Removal estimates for smaller streams
- Mark-Recapture estimates for larger streams
- Seasonal and spatial considerations
- Annual variation
- Importance of standardized methods
- Consult fisheries text

Age, Growth and Condition

What can we learn from aging fish?

- Sexual maturity
- Migration patterns
- Dietary shifts
- Life span
- Growth pattern
- Linkage to environmental variables

Using Length-Frequency Histograms



Holden 1999

Length-Frequency Histograms

- Easily applied tool
- Size range
- Size distribution
- Identifying cohorts
- Growth rate estimates
- Survivor estimates

Fish Condition

- Relating fish weight to length

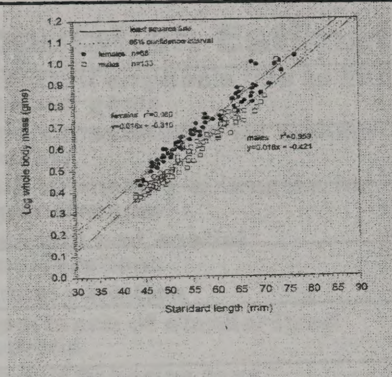


Figure 4. Standard length-whole body mass relationship for Rio Grande silvery minnow

USFWS 1999

Fish Condition

- Relating fish weight to length
- How does the condition of your fish stack up?

$$K=(W*X)/L^3$$

Where K= condition factor

W = weight (g)

L = length (mm)

X = constant (10^5)

Fish Condition

- Relating fish weight to length
- How does the condition of your fish stack up?
- Concept of "relative condition"

$W_r = W/W_s * 100$

W_r = relative weight of fish

W = actual weight of fish

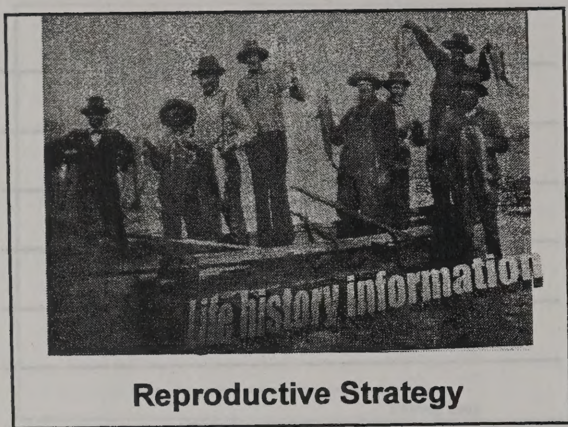
W_s = standard weight of fish of measured length

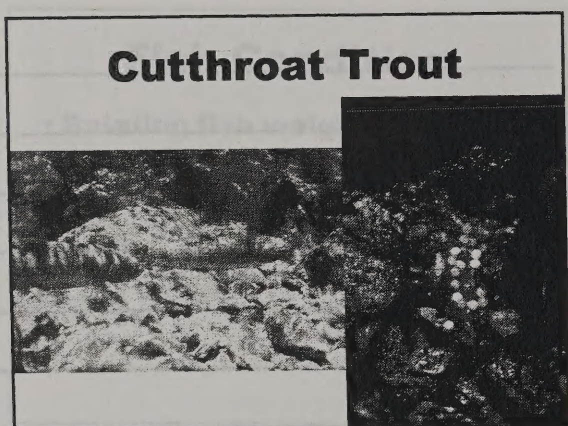
(75th percentile weight for species)

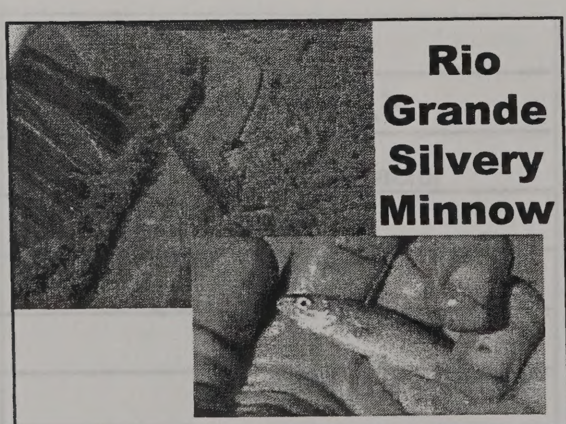
$W_r > 100$ indicates excellent condition

Fish Condition

- Relating fish weight to length
- How does the condition of your fish stack up?
- Concept of "relative condition"
- Spatial and temporal variation

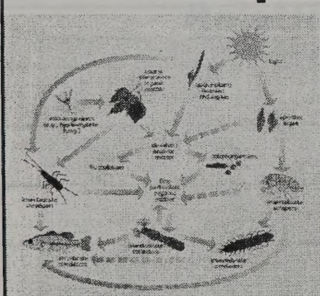

Life history information
Reproductive Strategy


Cutthroat Trout


Rio
Grande
Silvery
Minnow

Food Requirements

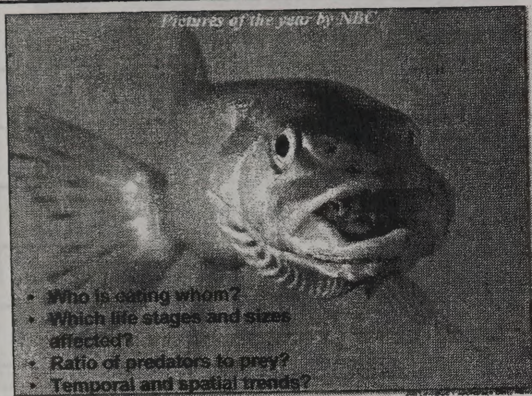
Food Requirements

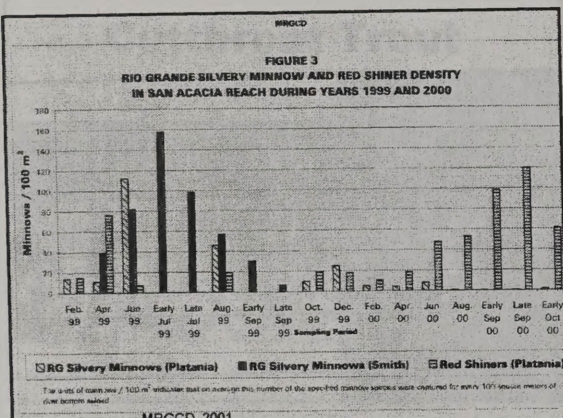


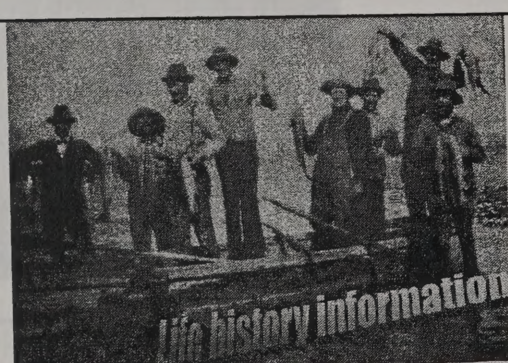
- Where in the food chain?
- How do Cutthroat and RGSM differ?
- Species and life stage competition?
- Temporal and spatial trends in condition?

FISRWG 1998

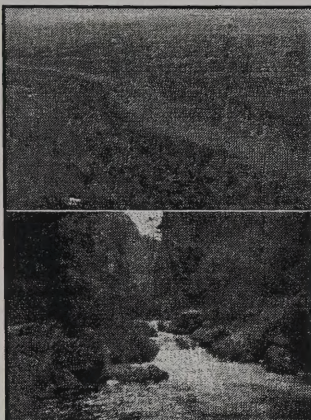
Predator – Prey Relations







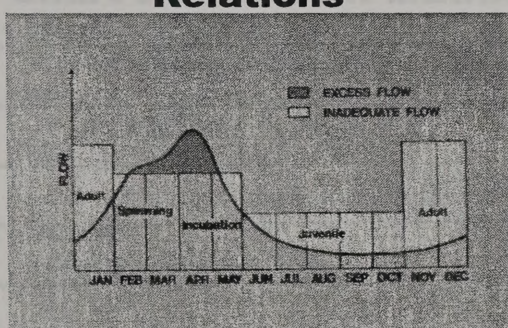
Habitat requirements by life stage



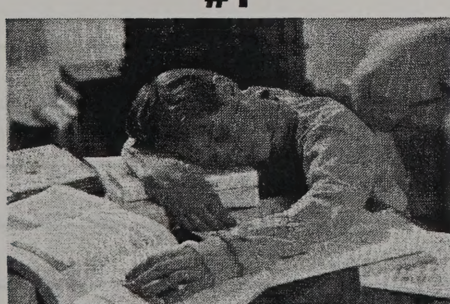
Physical Habitat Requirements

- Quantity and Quality
- Timing critical
- All life stages
  - Spawning and incubation
  - Larval stages/fry development
  - Juvenile
  - Adult

Cutthroat Habitat-Flow Relations



In-Class Problem #1

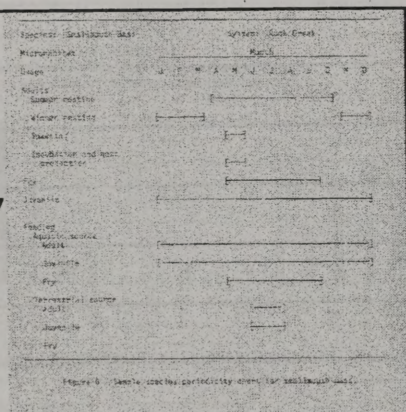


Building a Periodicity Chart and Habitat Matrix

- **Step 1**
  - Review habitat use for cutthroat (See HSI handout)
- **Step 2**
  - Build periodicity chart for species

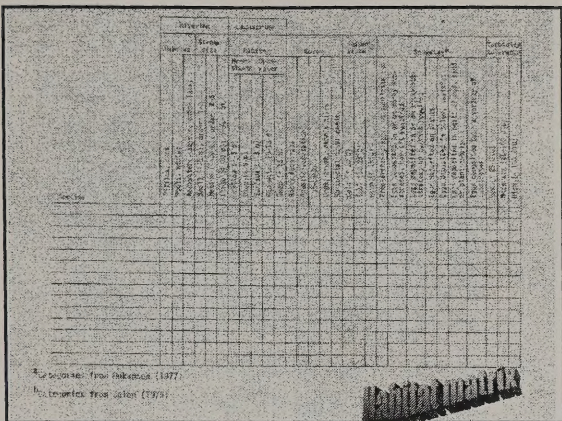
Example of Periodicity Chart

(Handout)



Building a Periodicity Chart and Habitat Matrix

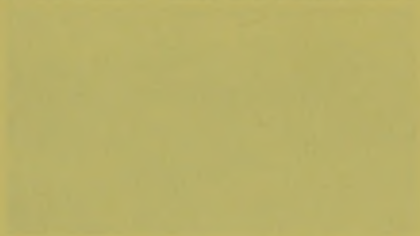
- **Step 1**
  - Review habitat use for cutthroat (handout)
- **Step 2**
  - Build periodicity chart for species
- **Step 3**
  - Complete a guild descriptor matrix for species (handout)



Building a Periodicity Chart and Habitat Matrix

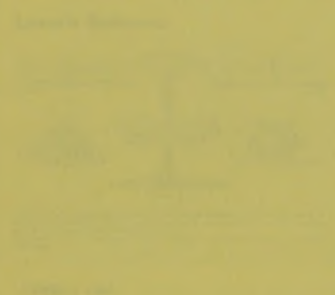
- **Step 1**
  - Review habitat use for cutthroat
- **Step 2**
  - Build periodicity chart for species
- **Step 3**
  - Complete a guild descriptor matrix for species
- **Step 4**
  - Discuss and compare results

Developing your habitat information



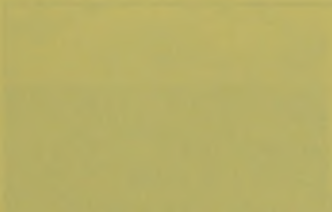
Where and when is it shallower?

Basic Watershed Function

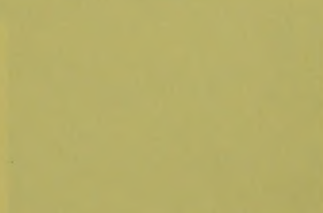


- Provides water and sediment
- How watershed processes water and sediment determines habitat

Intuitive Watershed-Habitat Relations



Look at the watershed, think of the stream!

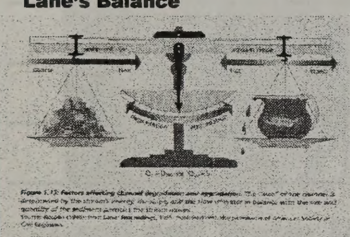


Developing your habitat information

Where and when is it available?

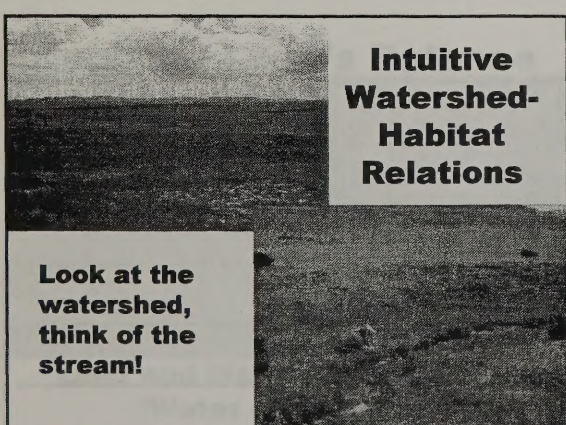
Basic Watershed Function

Lane's Balance



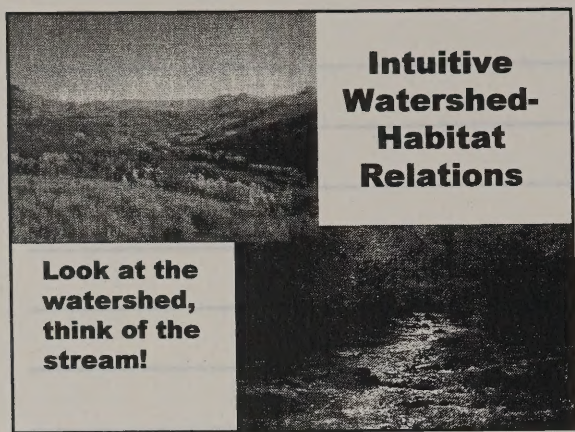
FISRWG 1998

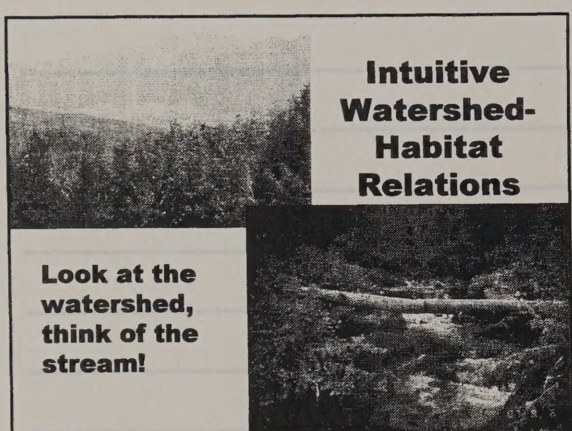
- Produce water and sediment
- How watershed processes water and sediment determines habitat

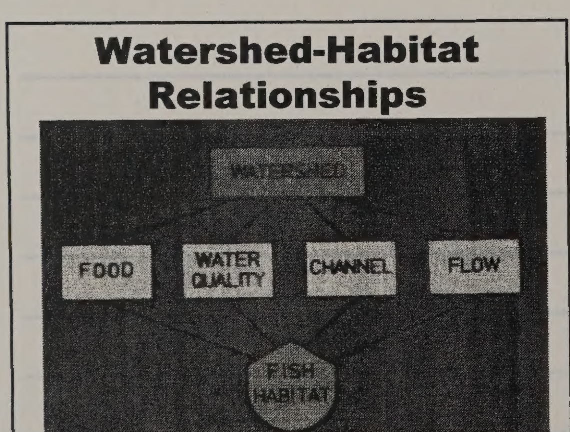


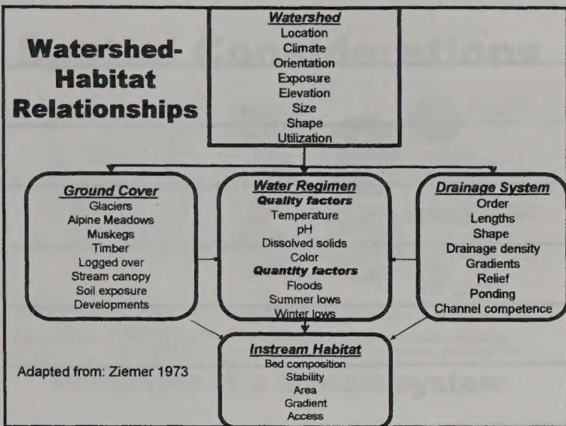
Intuitive Watershed-Habitat Relations

Look at the watershed, think of the stream!

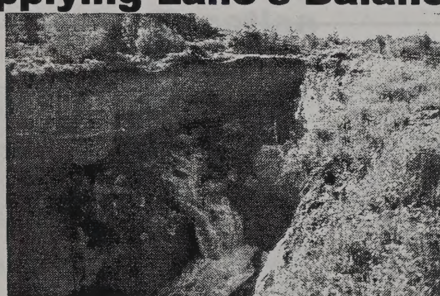

Intuitive Watershed-Habitat Relations
Look at the watershed, think of the stream!


Intuitive Watershed-Habitat Relations
Look at the watershed, think of the stream!


Watershed-Habitat Relationships
WATERSHED
FOOD
WATER QUALITY
CHANNEL
FLOW
FISH HABITAT

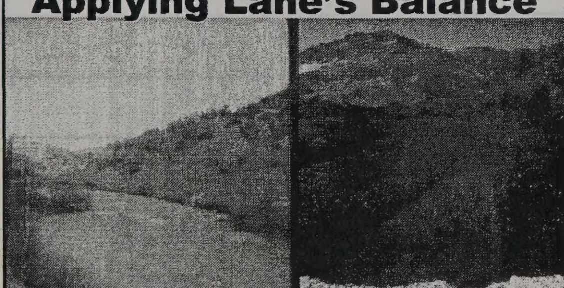


Applying Lane's Balance



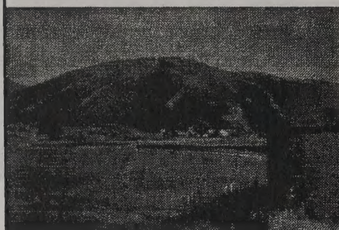
Land and Water Use Effects
"Flow augmentation"

Applying Lane's Balance



Land and Water Use Effects
"Water diversion"

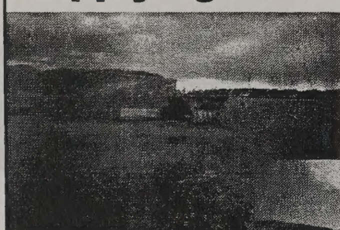
Applying Lane's Balance



Land and Water Use Effects

"Sediment loading"

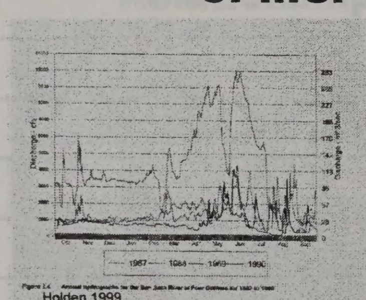
Applying Lane's Balance



Land and Water Use Effects

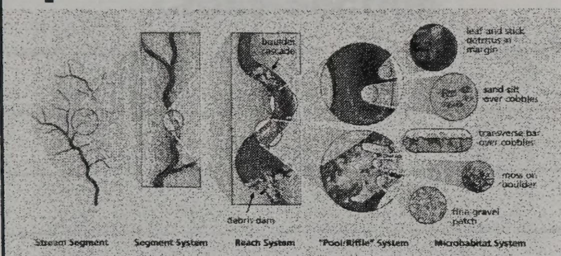
"Water and sediment storage"

Variability is a way of life!



- Temporal
- Spatial

Spatial Considerations



FISRWG 1998 *Figure 2.32: Hierarchical organization of a stream system and its habitat subsystems. Approximate linear spatial scale, appropriate to second- or third-order mountain stream.*

Hierarchy of a stream system

Watershed Longitudinal Zonation

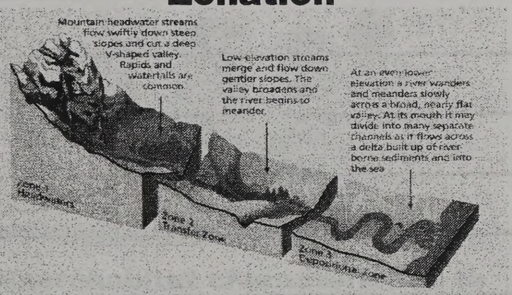


Figure 1.27: Three longitudinal profile zones. Channel and floodplain characteristics change as rivers travel from headwaters to mouth.
Source: Miller (1990). ©1990 Wadsworth Publishing Co.
FISRWG 1998

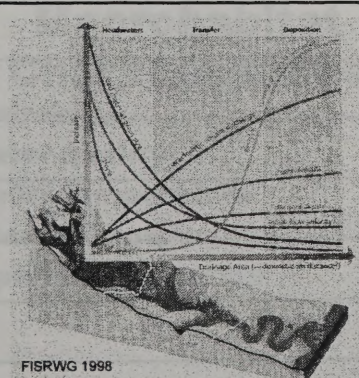


Figure 1.28: Changes in the channel in the three zones. Flow, channel size, and sediment characteristics change throughout the longitudinal profile.

Changing biology with changing zones –

The River Continuum Concept

FISRWG 1998

Latitudinal Zonation

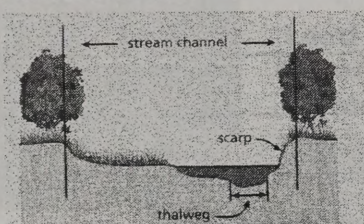
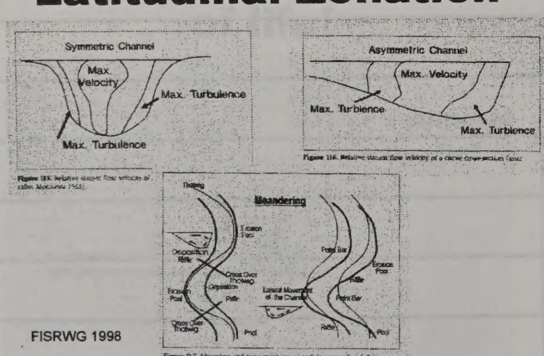


Figure 1.12: Cross section of a stream channel. The scarp is the sloped bank and the thalweg is the lowest part of the channel.

FISRWG 1998

Latitudinal Zonation



FISRWG 1998

More Complex River Cross-Section

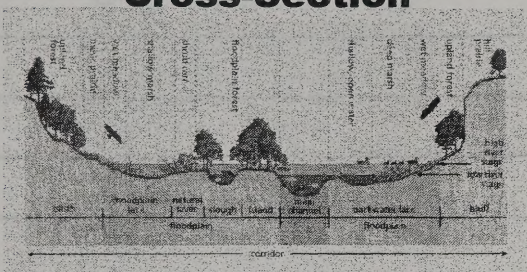
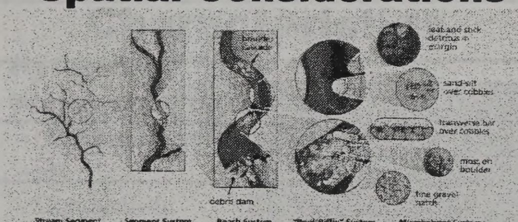


Figure 1.11: A cross section of a river corridor. The three main components of the river corridor can be subdivided by structural features and plant communities. (Vertical scale and channel width are greatly exaggerated.) FISRWG 1998

Source: Sparks. Bioscience, vol. 45, p. 170, March 1995. ©1995 American Institute of Biological Science

Spatial Considerations



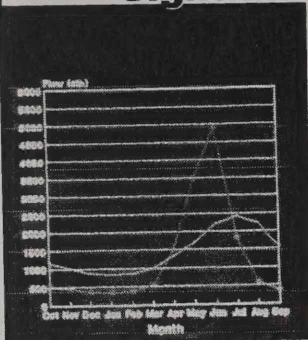
FISRWG 1998 *Figure 2.32: Hierarchical organization of a stream system and its habitat subsystems. Approximate linear spatial scale, appropriate to second- or third-order mountain stream.*

Macrohabitat characteristics to segment into reaches

Macrohabitat Characteristics

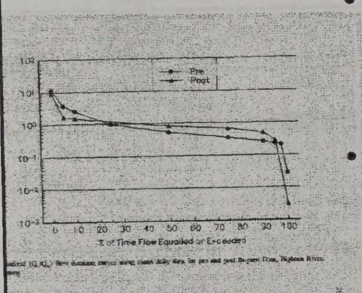
- **Hydrology**
- **Water quality**
- **Water temperature**
- **Channel morphology**
- **Riparian vegetation**

Hydrology "Signature flows"



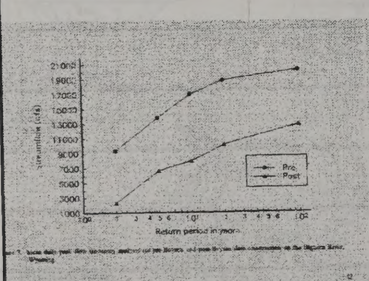
- Q_{aa}, average discharge or average annual flow
- Inflows/outflows
- Impoundments

Hydrology "Signature flows"



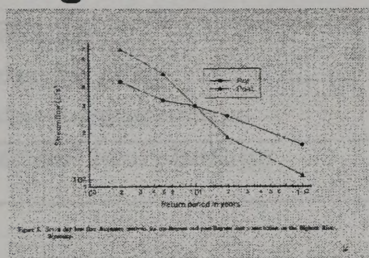
- Q_{10}, Q_{50}, Q_{90} – exceedence values from flow duration analysis
- Normalization

Hydrology "Signature flows"



- Flood frequency
  Q_{F2}
  Q_{F5}
  Q_{F25}

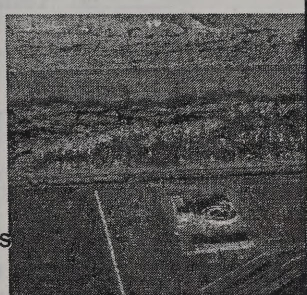
Hydrology "Signature flows"

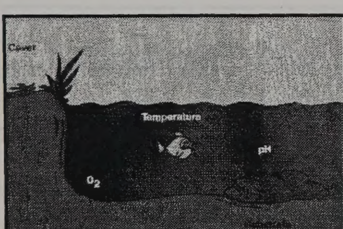


- **Low flow frequency – Q_{7L10}**

Macrohabitat Characteristics

- **Hydrology**
- **Water quality**
  - Dissolved oxygen
  - pH
  - Conductivity
  - Nutrients
  - Toxics
  - Macroinvertebrates





Water Quality

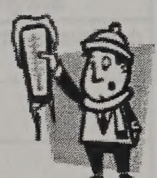
Dissolved oxygen
pH
Conductivity
Nutrients
Toxics

Macroinvertebrates Indices of WQ

- Taxa richness
- EPT ratio
- % dominant taxa
- Diversity
- Collector-gatherers/scrapers
- Tolerance values

Macrohabitat Characteristics

- Hydrology
- Water quality
- Water temperature
  - Minimums
  - Maximums
  - Means
  - Target species criteria



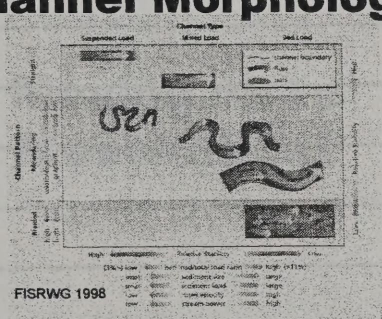
Optimal Temperature Varies by Species and Life Stage

Life Stage	Cutthroat Trout (Hickman and Raleigh 1982)	Channel Catfish (McMahon and Terrell 1982)
Adult	12-15^0 c	26-29^0 c
Spawning	6-17^0 c	21^0 c (min)
Embryo	9-11^0 c	15.5-29.5^0 c
Fry	<18^0 c	29-30^0 c

Macrohabitat Characteristics

- Hydrology
- Water quality
- Water temperature
- Channel morphology

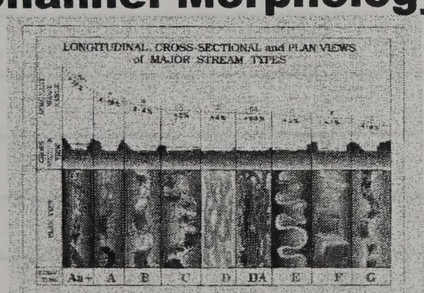
Channel Morphology



FISRWG 1998

Schumm Classification

Channel Morphology

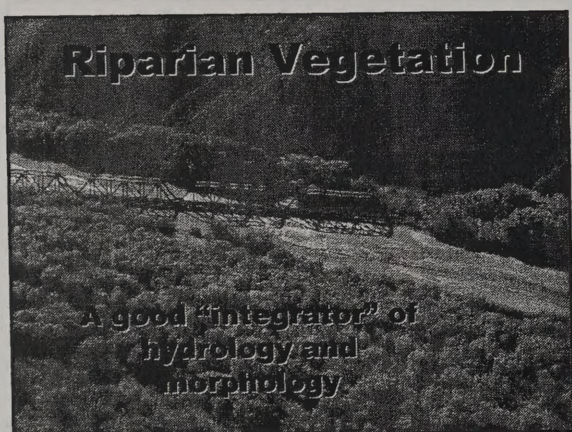


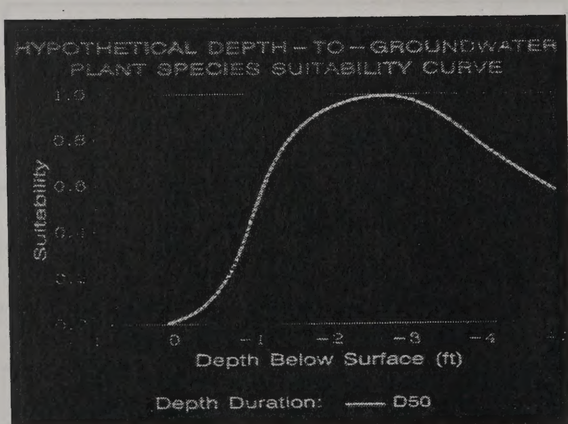
FISRWG 1998

Rosgen Classification

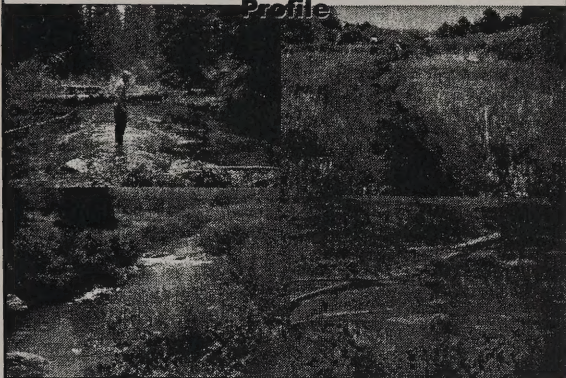
Macrohabitat Characteristics

- Hydrology
- Water quality
- Water temperature
- Channel morphology
- Riparian vegetation



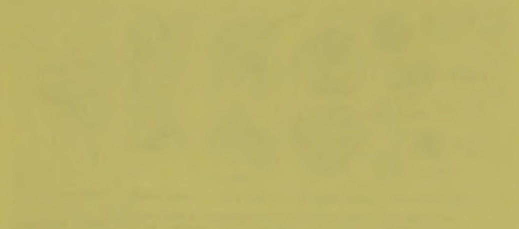


Vegetation Progression Along Channel Profile



Moving on to Mesohabitat

Spatial Considerations



Mesohabitat characterization to stratify the reaches

Mesohabitat

"Distinct hydro-morphological units spatially arranged within a stream reach and generally differing in water depth, velocity, cover, and fish habitat suitability characteristics."

Mesohabitat

- What is it?
- Spatial scale broader than microhabitat, but narrower than macrohabitat
- Allow better identification of community-level habitat use patterns

Spatial Considerations

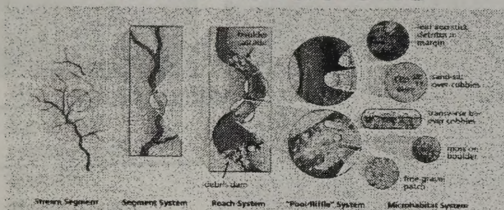


Figure 2.32: Hierarchical organization of a stream system and its habitat subsystems. Approximate linear spatial scale, appropriate to second- or third-order mountain stream.

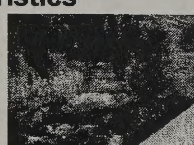
FISRWG 1998

Mesohabitat characteristics to stratify the reaches

Mesohabitat

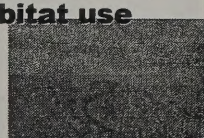
"Distinct hydro-morphological units spatially arranged within a stream reach and generally differing in water depth, velocity, cover, and fish habitat suitability characteristics"

Parasiewicz 2001



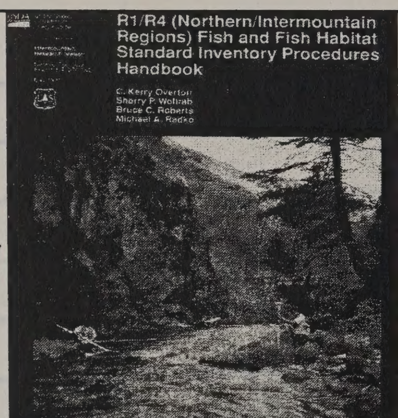
Mesohabitat

- What is it?
- Spatial scale broader than microhabitat, but narrower than macrohabitat
- Allow better identification of community-level habitat use patterns

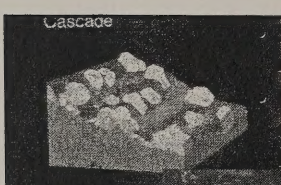


Types of Mesohabitats

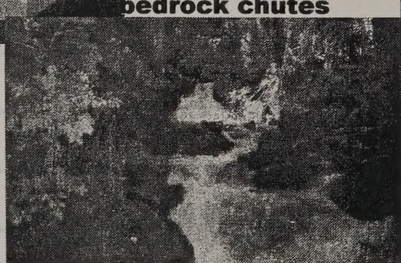
- **Numerous approaches**
- **Often tailored to stream and target species**
- **Basic units**
  - –Pool
  - –Riffle
  - –Run
- **Forest Service R1/R4 types**



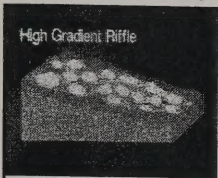
Overton et al, 1997

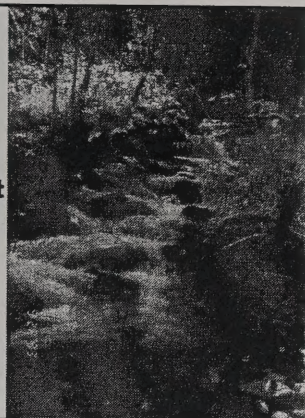


- **Steep gradient riffle (>7%)**
- **Composed of cascades, falls, bedrock chutes**



Overton et al, 1997



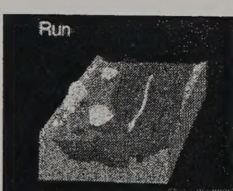


- Steep and swift
- Low to moderate depth
- Exposed substrate and broken water (white water)

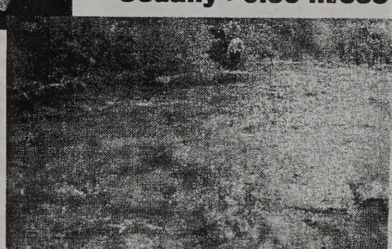
Overton et al, 1997

- Gradient <4%
- Surface agitation
- Substrate usually gravel and cobble dominate

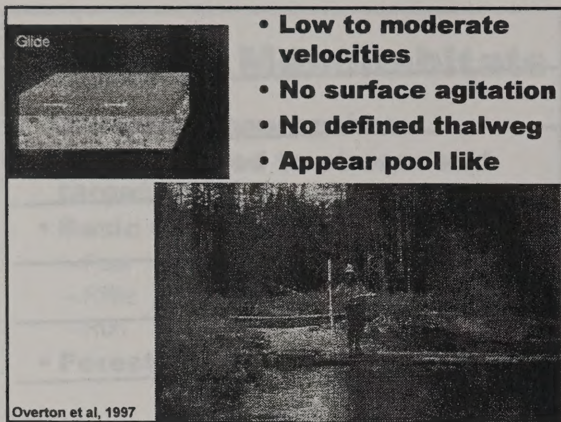
Overton et al, 1997

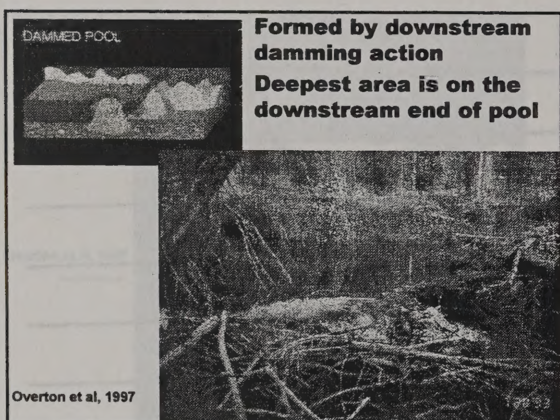


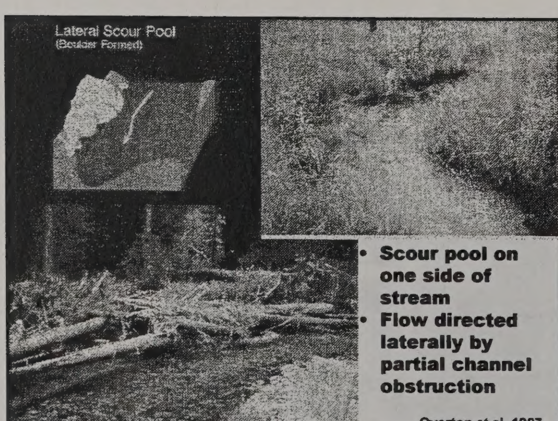
- Deep, fast with defined thalweg
- Little surface agitation
- Usually >0.30 m/sec

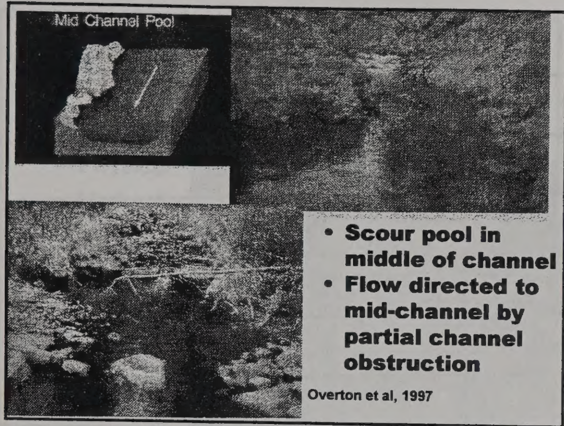


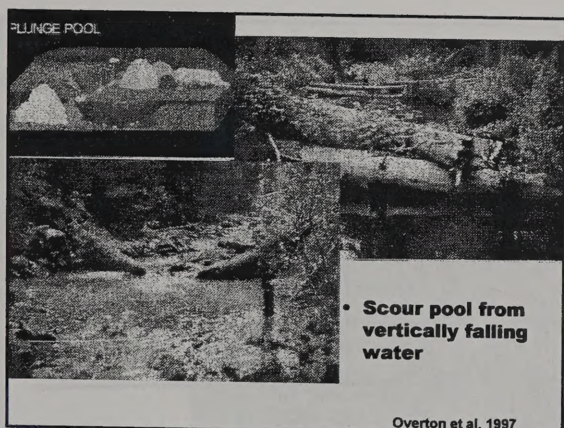
Overton et al, 1997

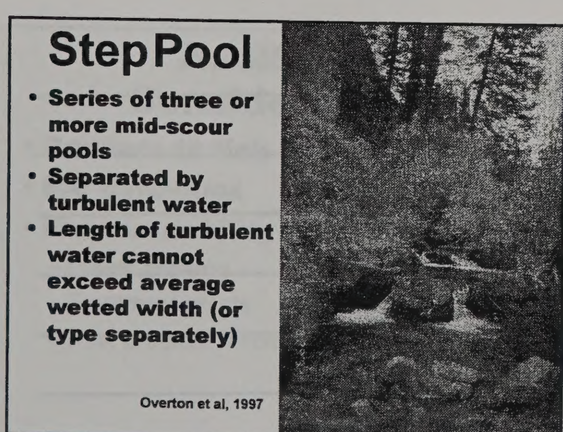

Glide
• Low to moderate velocities
• No surface agitation
• No defined thalweg
• Appear pool like
Overton et al, 1997


DAMMED POOL
Formed by downstream damming action
Deepest area is on the downstream end of pool
Overton et al, 1997


Lateral Scour Pool
(Boulder Formed)
• Scour pool on one side of stream
• Flow directed laterally by partial channel obstruction
Overton et al, 1997


Mid Channel Pool
• Scour pool in middle of channel
• Flow directed to mid-channel by partial channel obstruction
Overton et al, 1997


PLUNGE POOL
• Scour pool from vertically falling water
Overton et al, 1997

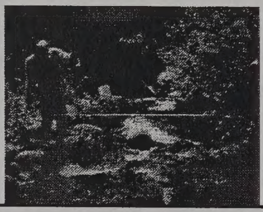

StepPool
• Series of three or more mid-scour pools
• Separated by turbulent water
• Length of turbulent water cannot exceed average wetted width (or type separately)
Overton et al, 1997

Microhabitat Commonly includes:

- Water depths
  - Minimum
  - Maximum
  - Mean
- Water velocities
  - Mean
  - Nose
  - Bottom
- Substrates
  - Dominant
  - Frequency distribution
  - Embeddedness
- Cover
  - Types
  - Availability
  - Fish access

Sampling Microhabitat

- Within all, critical, or representative mesohabitats
  - Cross-channel transects
  - Grid
  - Random

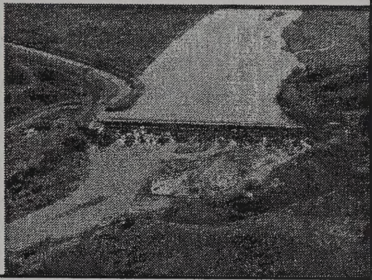


Spatial Considerations

- Longitudinal zonation
- Latitudinal zonation
- Macrohabitat
- Mesohabitat
- Microhabitat
- Additional considerations

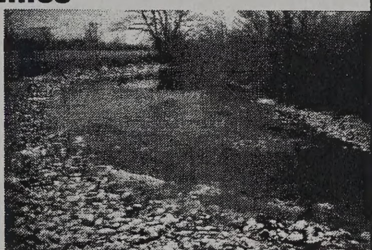
Additional Considerations

- **Barriers to fish movement**
  - Physical
  - Hydraulic



Additional Considerations

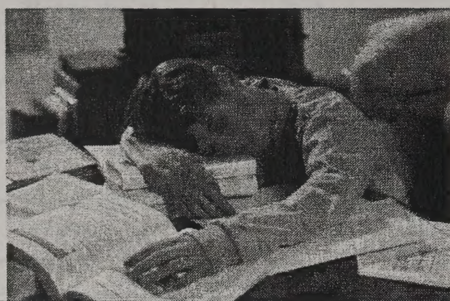
- **Barriers to fish movement**
- **Ice dynamics**
  - Shelf
  - Frazil
  - Anchor



Additional Considerations

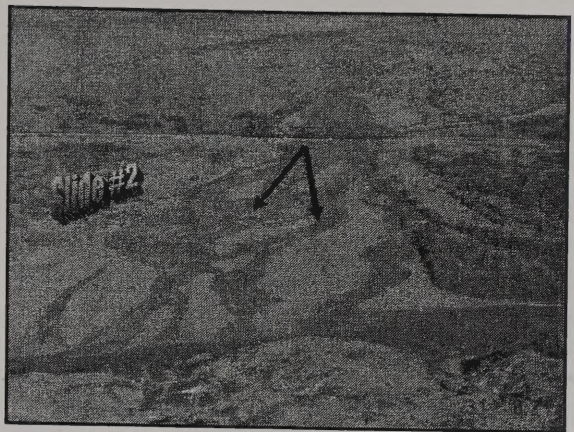
- **Barriers to fish movement**
- **Ice dynamics**
- **Flow variability**
  - Power peaking
  - Treatment plants
  - Real problem if comparing reaches

In-Class Problem #2
Slide Quiz!!

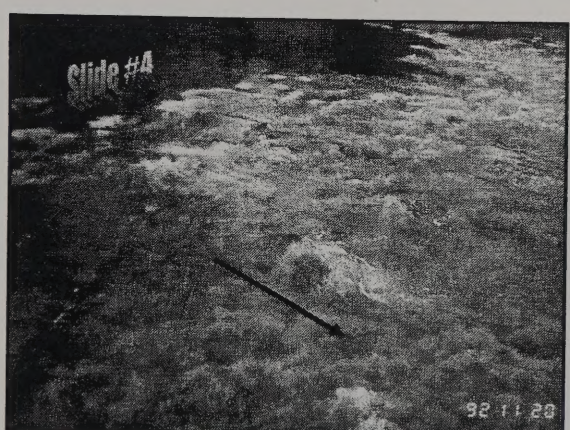


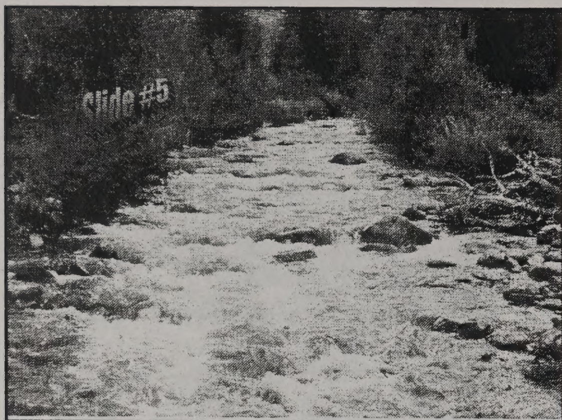
In Class Slide Quiz

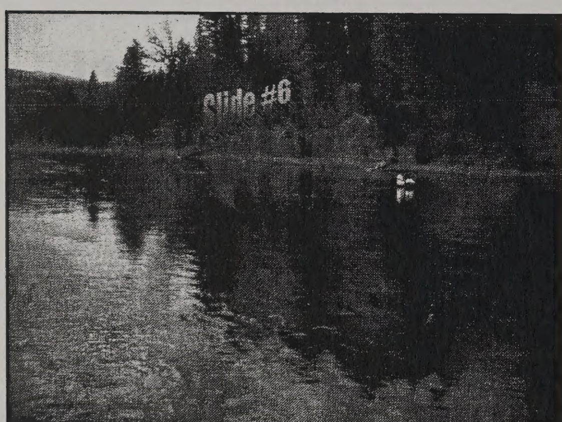
- Identify instream habitat features
- 10 slides will be shown
- Answer multiple choice questions
- Self graded review

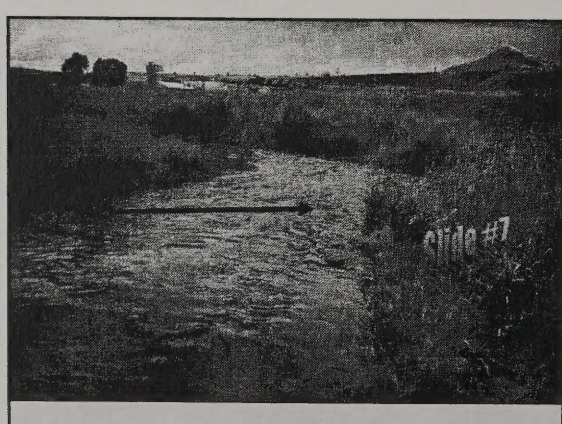

Slide #2

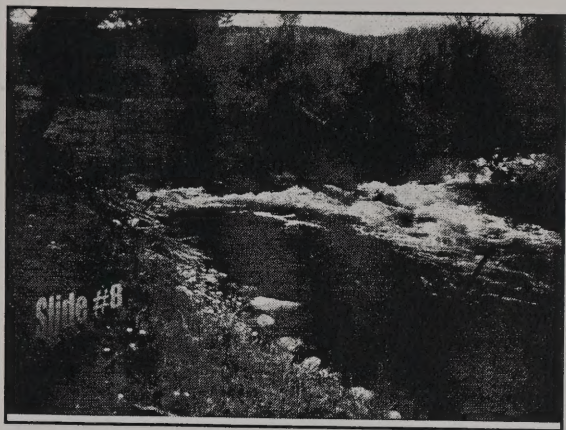

Slide #3


Slide #4
92 11 28

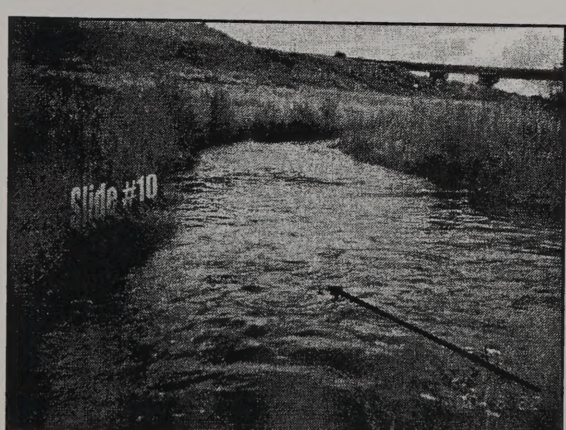

Slide #5


Slide #6


Slide #7


Slide #8

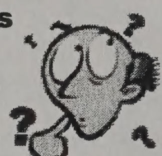

Slide #9


Slide #10

Morning Wrap-up

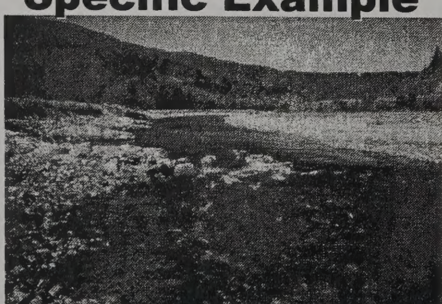
- Designing your habitat study from the watershed down
- Most every study is somehow unique

Important Considerations



- Specific objectives
- Time
- $$$$$$$$$
- Manpower
- Sampling protocols

Specific Example



Coeur d'Alene River, Idaho

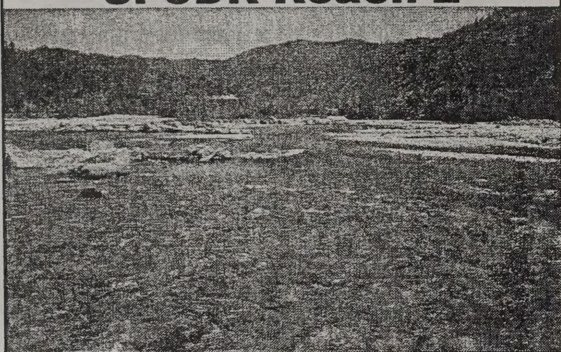
South Fork Coeur d'Alene River

- **Objective**
  - Develop a preliminary physical habitat restoration plan for salmonids in 20+ miles of stream
- **Considerations**
  - Important to personally observe entire length
  - Tight schedule
  - Reaches stratified by hydrology, WQ, morphology, and land use

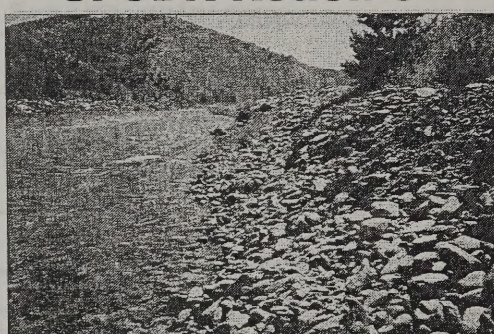
SFCDR Reach 0

SFCDR Reach 1

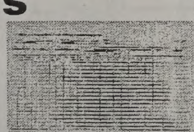
SFCDR Reach 2



SFCDR Reach 3



Habitat Survey Protocols

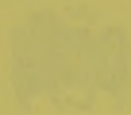


- **Handout of survey forms**
- **Desired characteristics**
  - Rapid
  - Thorough
  - Defensible
- **Hybrid of FS Basin-wide and MT TMDL**
- **Basic sampling unit – mesohabitat**
- **Sampling rate of 1-2 miles per day**
- **Only one person for continuity**
- **Qualitative and quantitative assessment**

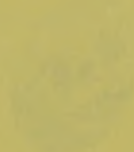
Day 1

Assessment of Fish Needs

- Identifying "target" species
- Developing information for "target" species
- Developing habitat information
- Putting it all together



Afternoon Workshop



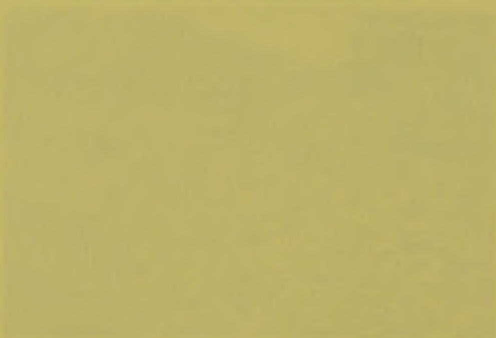
"Putting it all together – the search for bottlenecks"

What is a Limiting Factor?

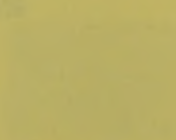
- "Any condition that approaches or exceeds the limits of tolerance by an organism"
- "A habitat component whose quantity constrains or limits the size of a population"
- Can be biological, chemical or physical

SFCDR Reach 2

SFCDR Reach 3



Habitat Survey Protocols



Day 1

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Afternoon Workshop

"Putting it all together – the search for bottlenecks"

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- "A habitat component whose quantity constrains or limits the size of a population"
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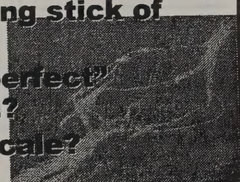
Armantrout 1998

Afternoon Workshop

- Reference stream approach
- Potential limiting factors
  - Temperature (SSTEMP)
  - Physical habitat (HEP/HSI)

Reference Stream Approach *Pro's and Con's*

- Definition
  - "A stream similar in character to the test stream, absent the disturbance"
- Provides measuring stick of what could be
- Is there ever a "perfect" reference stream?
- At what spatial scale?



Types of Reference Streams

- Historical comparisons

Historical Comparisons

- Usually first choice
- Data often hard to find

Types of Reference Streams

- Historical comparisons
- Upstream/downstream comparisons

Upstream/Downstream

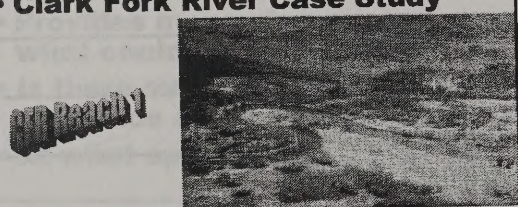
- Usually second choice
  - Downstream complicated by upstream
  - Upstream complicated by differing watershed conditions

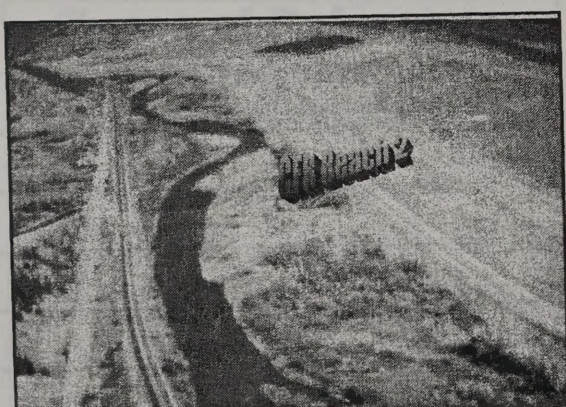
Types of Reference Streams

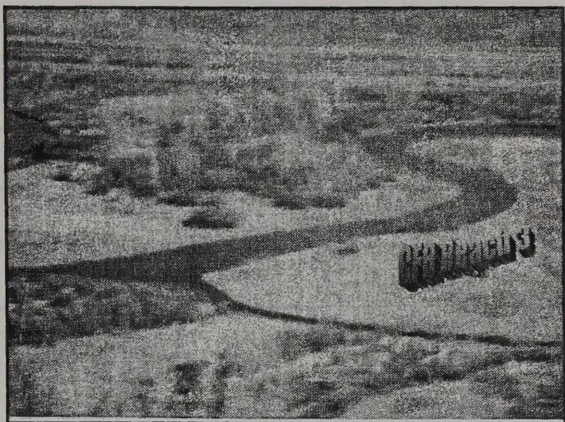
- Historical comparisons
- Upstream/downstream comparisons
- Paired watersheds

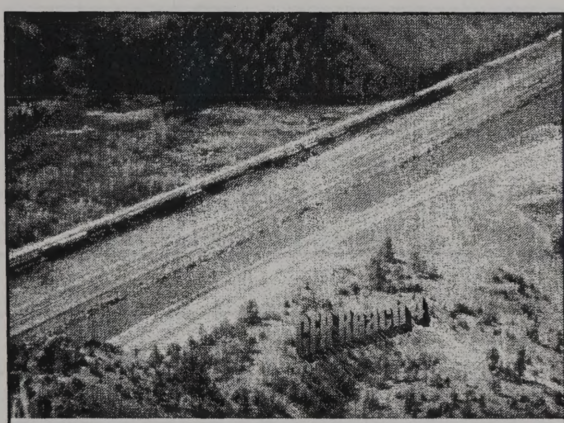
Paired Watersheds

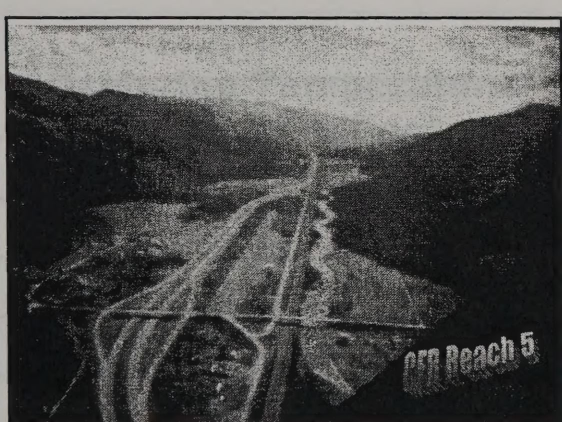
- Usually 3rd Choice
- Most commonly used
- Clark Fork River Case Study

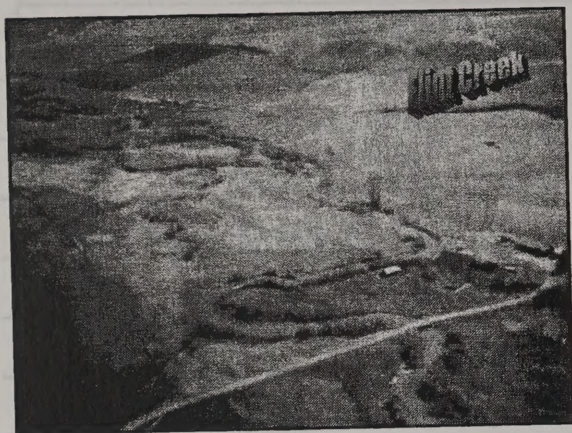


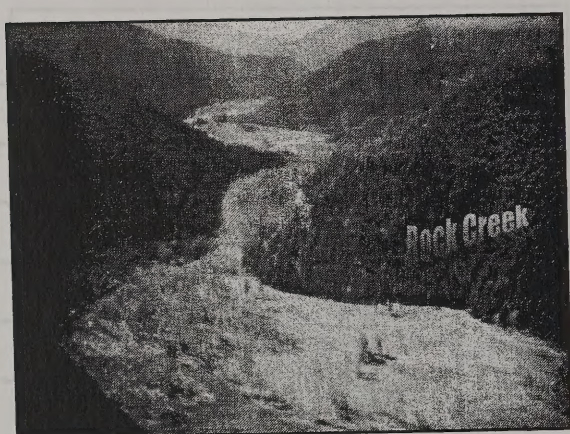







OFR Reach 5


Creek

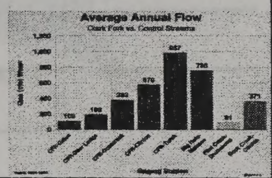

Rock Creek


Hole River

In-Class Problem #3

How Close is Close Enough?

- Review comparison plots
- Develop decision matrix
- Select reference for each CFR reach
- Discuss results

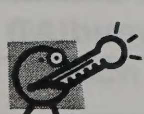


Afternoon Workshop

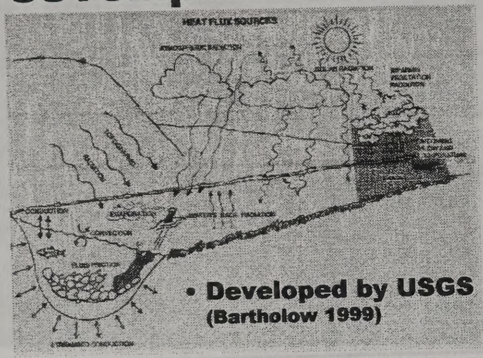
- Reference stream approach
- Potential limiting factors
  - Temperature (SSTEMP)
  - Physical habitat (HEP/HSI)

Exploring Temperature as a Limiting Factor

SSTemp for Windows



SSTemp for Windows



- Developed by USGS
  (Bartholow 1999)

SSTemp for Windows

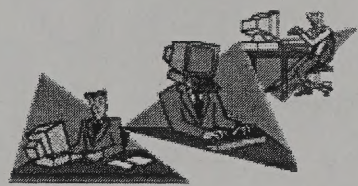
- Developed by USGS
- Scaled down version of SNTemp
- Single stream segment for single time period
- Estimates min, max and mean temps
- Allows for evaluation of flow, shading and morphology alternatives
- Software relatively easy to use!

SSTemp for Windows Availability

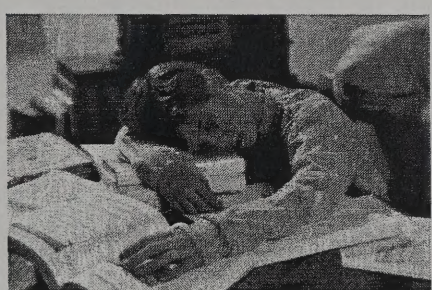
Download – Free
www.mesc.usgs.gov
Products, Software and Predictive models

Mid-Continent Ecological Service Center
Version 1.0.0 Revised April 1999
Ft. Collins, CO

Walk Through of SSTemp Software



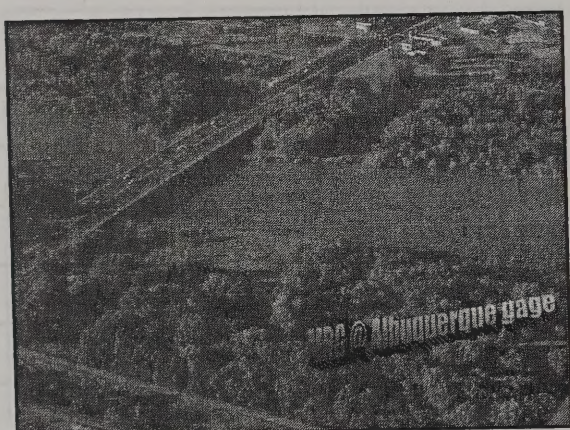
In Class Problem #4



Evaluating water temperature as a potential limiting factor for RGSM in the Middle Rio Grande River @Albuquerque to Isleta Reach using SSTemp

Class SSTemp Problem

- Pair off
- Review aerial photos



Class SSTemp Problem

- Pair off
- Review aerial photos
- Information provided
  - Flow
  - Temperature
  - Channel morphology
  - RGSM temperature preferences
- Complete and discuss results

Habitat as a Limiting Factor

Habitat Evaluation Procedures (HEP)

Habitat Suitability Indices (HSI)

HEP/HSI

- Developed by USFWS in 1980's
- Species and life stage specific
- Based on 2 ecological principles
  - Habitat has a definable carrying capacity to support wildlife
  - Habitat suitability for a species can be estimated based on measurable vegetative, physical and chemical traits
- Basic unit of measure is Habitat Unit
  where: HU= AREA * HSI

General Uses of HEP

- Assess impacts of land and water development
- Allows two types of comparisons
  - Different areas at same point in time
  - Same area at different points in time

HEP is the general accounting system for assessing impacts, while HSI is the species-specific technical model for quantifying habitat quality

HSI

- Suitability described on scale of 0 (unsuitable) to 1 (optimum)
- Developed/applied for species, life stages, guilds, and/or communities
- Specific field methods left to investigator
- Localized habitat use info can be substituted

Restoration Uses of HEP/HSI

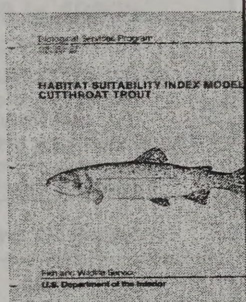
- Identify potential limiting factors
- Compare existing habitat between candidate reaches/sites
- Assess habitat impacts due to historic uses
- Estimate future habitat gains from possible restoration strategies

HEP/HSI Availability

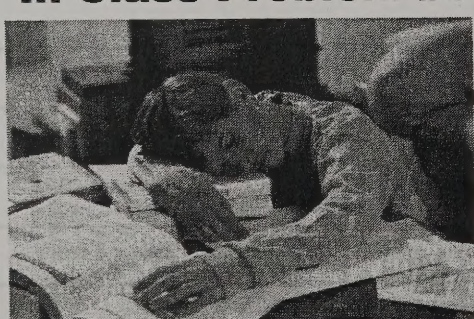
- **HEP/HSI Publications**
  - www.mesc.usgs.gov
- **Blue Books** online (National Wetlands Research Center)
  - www.nwrc.gov/wdb/pub/hsi/hsiindex.htm
- Computer Software
  - **HEP – DOS version, unsupported**
    - www.mesc.usgs.gov/products/software
    - windows version coming "soon"
  - **HSI - DOS version, unsupported**
    - www.mesc.usgs.gov/products/software
    - No windows version planned

Walk Through of Cutthroat Trout HSI Model

- **Handout**
- **Habitat requirements**
- **Model components**
- **Suitability graphs**
- **Component scores**
- **Overall HSI score**



In Class Problem #5



Identifying Limiting Factors using Cutthroat HSI

- Group 1 – Calculate HSI for reference stream
- Group 2 – Calculate HSI for test stream
- Discussion
  - Score variation
  - Identified limiting factors
  - Possible management actions
  - Objective statements

Day One Wrap-Up!

Day 2
Instream Flow

BLM TRAINING COURSE No. 7000-12
AQUATIC HABITAT RESTORATION & ENHANCEMENT
August 5 - 9, 2002
Albuquerque, NM

DAY TWO: Habitat Restoration Analysis & Design - The Basic Ingredient, WATER!

- Review and clean-up from Day One (15 minutes)
- Instream Flow, an issue that's changed the West (and beyond)! (30 minutes)
  - ✓Where have we been?
  - ✓Where are we now?
  - ✓Where are we headed?
- Exploring "Flow" as a potential limiting factor (2 hrs, 15 minutes)
  - ✓Brief review of "signature flow" comparisons, SSTEMP, HEP/HSI
  - ✓Indicators of Hydrologic Alteration (IHA)
    - ☺Video, "Managing River Flows for Biodiversity"
    - ☺Background & summary
    - ☺Walk-through of IHA software
    - ☺In-class Problem #6 - Using IHA to assess Middle Rio Grande flow changes
- Overview of Instream Flow Methods (1 hour)
  - ✓"Rule-of-thumb" approaches based on historical discharge records
  - ✓Single transect approaches ("critical" site analysis)
  - ✓Multiple transect one-dimensional approaches ("representative" site analysis)
  - ✓Two-dimensional modeling
  - ✓Maintenance of sediment transport & channel morphology
    - ☺Flushing flows - North Platte River case study
    - ☺Channel maintenance flows
    - ☺Riparian restoration flows
  - ✓"Mimicry" of a natural hydrograph - San Juan River case study

- **Lunch Break**

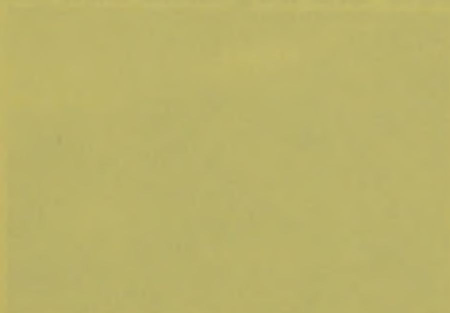
- **AFTERNOON WORKSHOP, "Developing Instream Flow Recommendations"**(4hr)
  - ✓Using WinXSPRO to analyze channel cross-sections & develop IF's
    - ☺Background & summary
    - ☺Getting to know the software (copy for each participant)
    - ☺In-class Problem #7 - Using WinXSPRO to develop IF recommendations
  - ✓Using RHABSIM to develop IF's for fisheries
    - ☺Background & summary
    - ☺Walk-through of field data collection
    - ☺Walk-through & demonstration of software
    - ☺In-class Problem #8 - Using RHABSIM output to evaluate IF trade-offs
  - ✓Designing a mitigative flushing flow regime - Deadman Creek case study
  - ✓Class discussion of IF applications

- Discussion and wrap-up for Day Two

Day 2
The Basic Ingredient: WATER

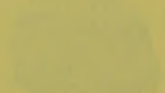
- Instream flow – an issue that has changed the West
- Recognizing flow as a limiting factor
- Overview of instream flow methods
- Workshop on developing instream flow recommendations

Instream flow – an issue that has changed the West

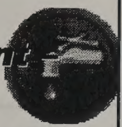


Instream Flow

"A flow or flow regime released or protected to maintain or support an identified instream value or use."

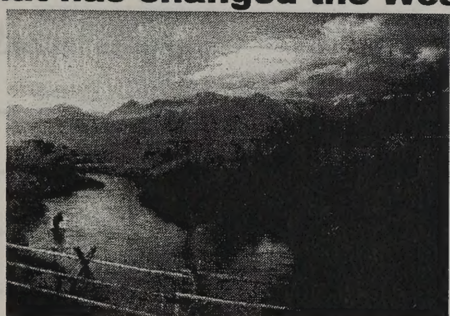


Day 2
The Basic Ingredient: WATER



- **Instream flow – an issue that has changed the West**
- **Exploring flow as a limiting factor**
- **Overview of instream flow methods**
- **Workshop on developing instream flow recommendations**

Instream flow – an issue that has changed the West



Instream Flow

"A flow or flow regime released or protected to maintain or improve an identified instream value or use."

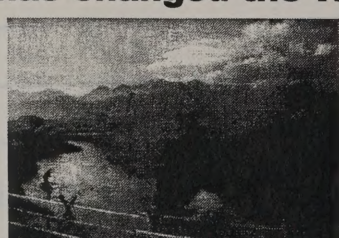
out-of-date perspective as we are interested in going out beyond the banks of a stream.

Instream flow – an issue that has changed the West

Where have we been?

First use of term was in the 50's
1960's instream flow movement began in ernest.
Keeping the stream "wet".

Instream flow – an issue that has changed the West



Where are we now?

"Dynamic" instream flows

- Instream flows for fisheries, WQ....
- Flushing flows in regulated systems
- Channel maintenance flows
- Riparian maintenance flows

Target flows go beyond a min.

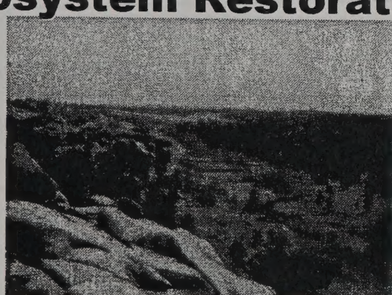
Instream flow – an issue that has changed the West

Where might we be headed?

?

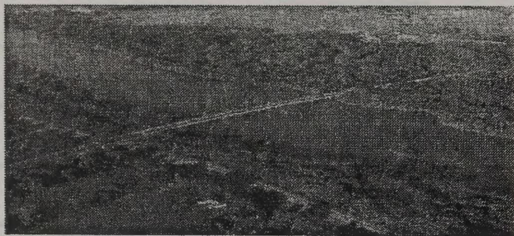
IHA - RBA exercise is an 'indicator.

Ecosystem Restoration

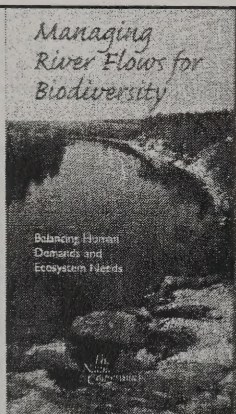


"Mimicry" of the natural hydrograph

Hydrology as a Limiting Factor



Indicators of Hydrologic Alteration (IHA Model)



Video Time

What is the RBA?

RVA

Range of Variability Approach

IHA Model

- Developed in mid 1990's by Nature Conservancy
- Tool for calculating hydrologic regime characteristics using *daily* streamflow, water stage, groundwater levels, or lake levels
- Analyze changes over time
- Identifies type and degree of change
- Converts *long term* data into 33 ecologically relevant parameters (See handout, Table 1)
- RVA (Range of Variability Approach) establishes target ranges for 33 parameters
- Software available

Indicators of Hydrologic Alteration
User's Manual

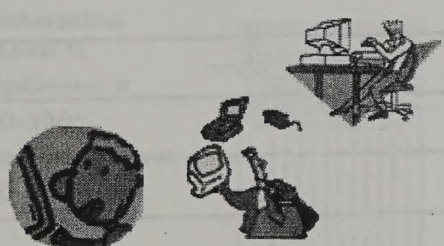
The Nature Conservancy

with
Smythe Scientific Software
July 2001

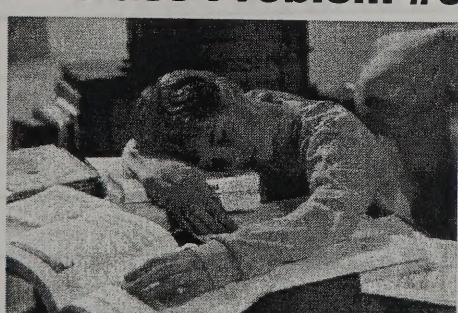
Availability of IHA

- Currently, free through Smythe Scientific Software or
- Nature Conservancy Web page
  www.freshwaters.org
- Chuck Smythe
  - csmythe@webaccess.net
  303-499-0222

Walk Through IHA Software



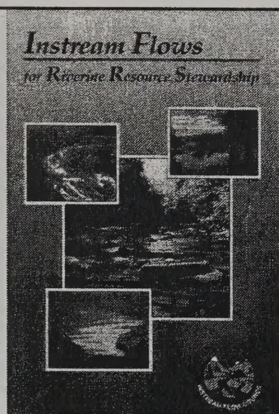
In-Class Problem #6



Analyzing Changes in MRG Hydrology using IHA

- Step 1- Review the problem
- Step 2 - Load and run IHA
- Step 3 - Review your IHA output
- Step 4 - Answer questions in problem
- Step 5 - Discussion

Overview of Instream Flow Methods



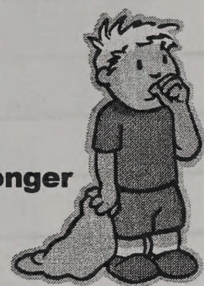
www.instreamflowcouncil.org
1-800-537-6727
$40 plus S&H
If any are left

IF Approaches

- Rule of thumb
- Single transect
- Multiple transect (1D)
- 2D modeling
- Sediment transport
- Hydrograph "mimicry"

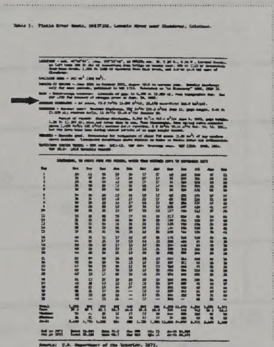
Rule of Thumb

- **Tennant Method**
  - **Average discharge**
- **Hoppe Method**
  - **Flow duration**
- **Seldom used any longer**



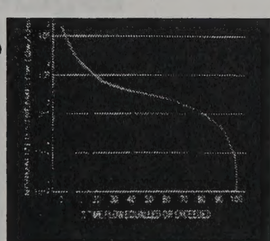
Tennant Method

- **Determine mean Q**
- **Optimum = 60-100%**
- **Late season = 20-40%**



Hoppe Method

- **Spawning $Q=Q_{40}$**
- **Rearing $Q=Q_{80}$**
- **Flushing $Q=Q_{17}$**

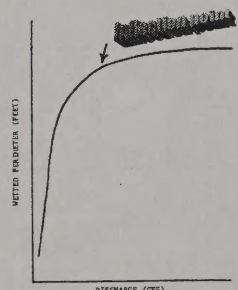


Single Transect (critical site analysis)

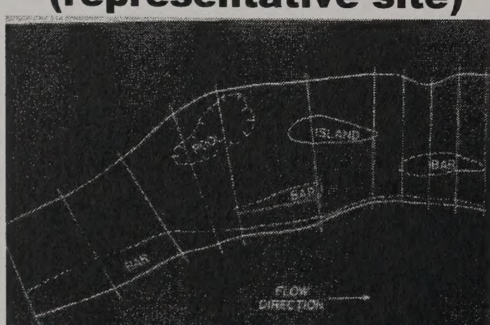
- Wetted perimeter
- Passage
- Spawning
- Rearing

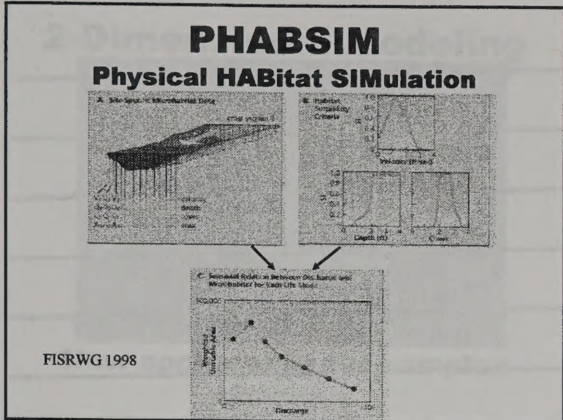
Wetted Perimeter

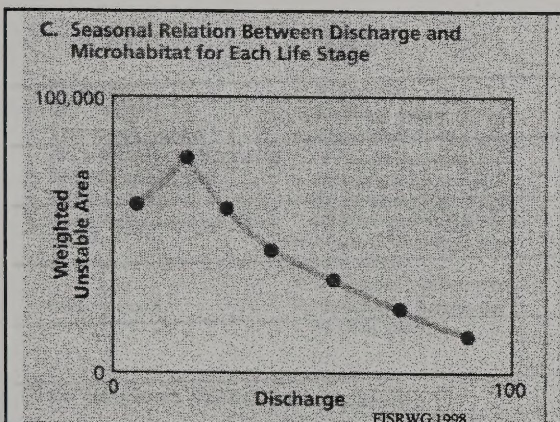
- Select shallow riffle x-section
- Measure/model at multiple flows
- Plot wetted perimeter-flow relationship
- Determine inflection point

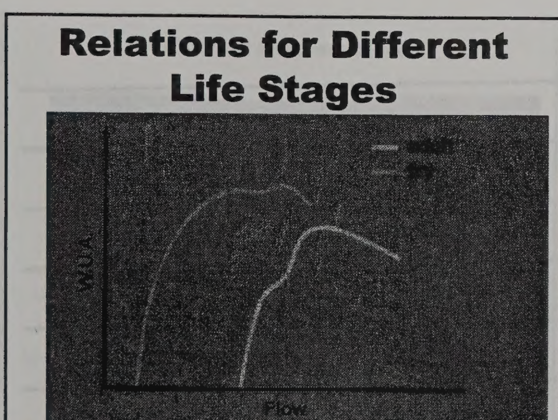


Multiple Transect (representative site)

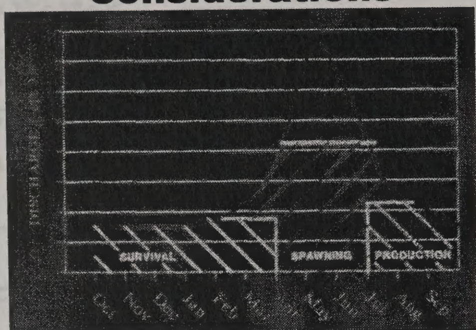



PHABSIM
Physical HABitat SIMulation
Discharge
FISRWG 1998


C. Seasonal Relation Between Discharge and Microhabitat for Each Life Stage
100,000
Weighted Unstable Area
0
0
Discharge
100
FISRWG 1998


Relations for Different Life Stages
WUA
Flow

Seasonal Considerations



PHabSim

- Available through
  - www.mesc.usgs.gov
- Cost = Free
- Classes available
- Even windows version has pretty steep learning curve

RHABSIM

Riverine HABitat SIMulation

RHABSIM
Riverine HABitat SIMulation software
Thomas R. Payne and Associates

- Developed by T. R. Payne & Associates
- More user friendly
- Windows Version
- Cost $895.00
- http://www.northcoast.com/~trpa

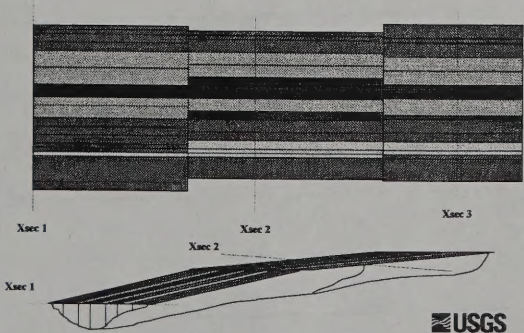
2-Dimensional Modeling

New approaches for complex channels

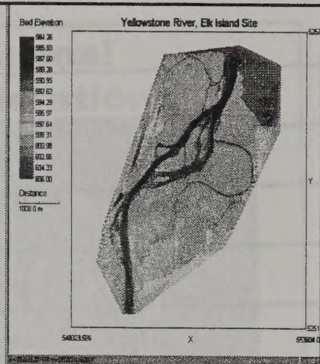
1D	2D
• PHABSIM	• River 2D
• 20+ years	• Cutting edge
• Transect based (D, velocity, substrate)	• Site based (terrain analysis)
• Simple channels	• Complex channel
• WUA output	• WUA w/mesohabitat option using ARCinfo
• Data collected at three flows	• Field intensive, but one time
	• Computer intensive
• Lower cost	• Hydraulic engineer
	• Higher cost

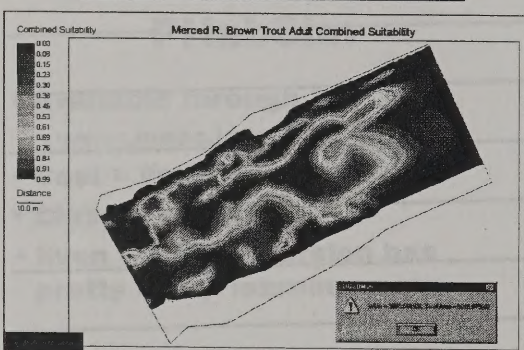
(See handout, Waddle et al, 2000)

1-D Habitat Representation

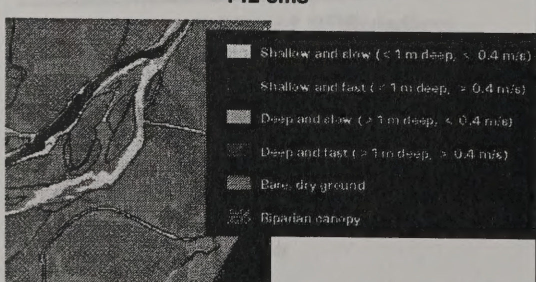


With 2-D Models, complex channels can be explicitly represented





Patches of Habitat, Elk Island, Yellowstone R., 142 cms



USGS

(See Parasiewicz, 2001, Handout)

2 Dimensional Habitat Modeling

Pros

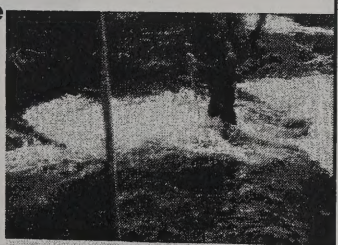
- Better than 1D at
  - Backwater
  - Islands
  - Flow shifts
  - Velocity distribution
- Covers area not transect
- Chance for more habitat metrics (ArcInfo)

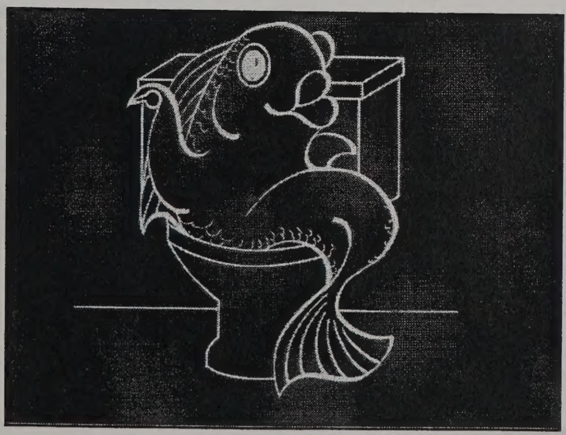
Cons

- Data intensive, increased costs
- Large computational costs
- Processing is slow (2 weeks on some complex channels)
- Steep learning curve plus need ArcInfo to visually present data
- Depth averaged
- Need hydraulic engineer's help

Sediment Transport

- Flushing
- Channel maintenance
- Riparian restoration

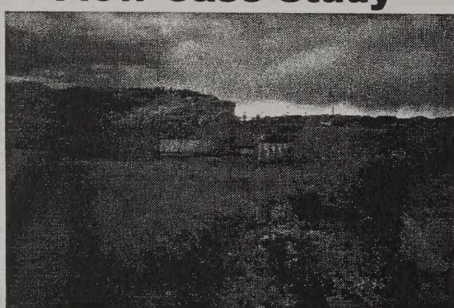


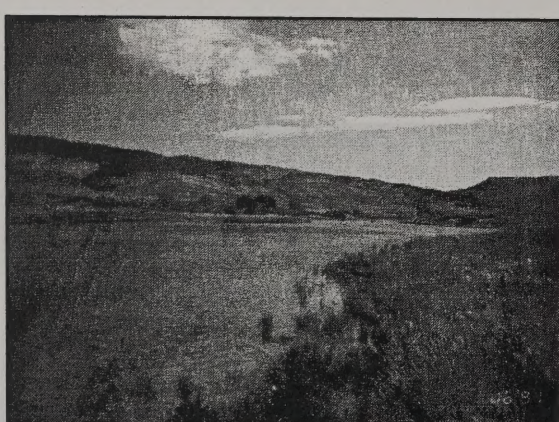


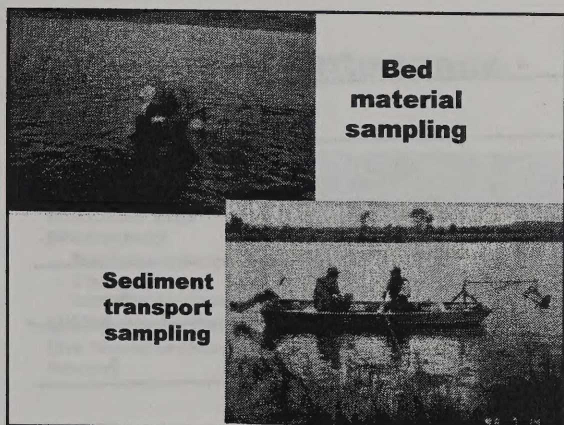
Flushing Flow

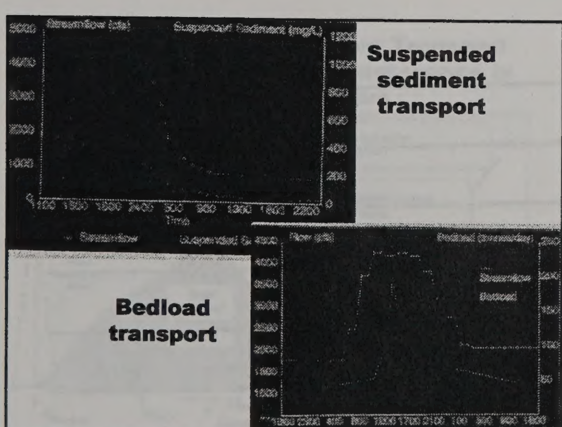
- Definition
  - Short duration
  - High magnitude
  - "Artificial" floods
- Uses
  - Effective below dams
  - Mitigation

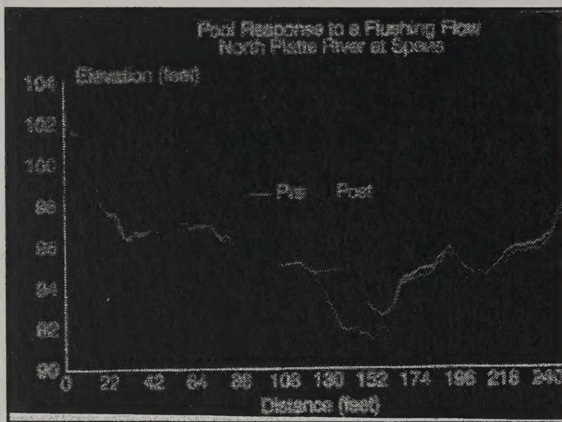
North Platte Flushing Flow Case Study

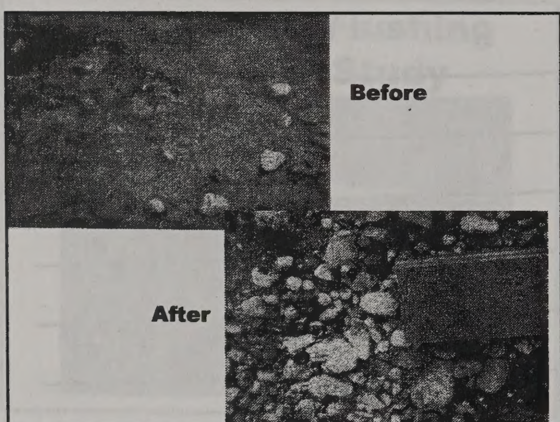





Bed material sampling
Sediment transport sampling


Suspended sediment transport
Bedload transport
Streamflow (cfs)
Suspended Sediment (mg/L)
Time


Pool Response to a Flushing Flow
North Platte River at Spears
Elevation (feet)
Pre
Post
Distance (feet)


Before
After

ROCKY MTN NEWS
SUNDAY, MARCH 19, 2000 pg 36C SPORTS
"FLUSH WITH TROUT"

North Platte fishery reborn as dam flows cleanse spawning area

Guide Mark Boname of Casper holds a 6-pound male rainbo[w] ...ical of the robust trout of the Gray Reef stretch of the North Pl[atte]

Ed Dentry

CASPER — Mark Boname wasn't the only driftboat oarsman searching for Walter on a breezy Sunday in east-central Wyoming.

Clearly, word has spread like prairie fire along the lower reaches of the North Platte River, where hills and canyons give way to windswept grasslands. Formerly a river reach mired in smothering silt, the North Platte from Gray Reef Dam to Casper is reborn.

Muck has mutated into scrubbed rocks and clean gravel spawning bars. Trout populations, particularly of rainbows, have expanded in the 30-mile stretch. Predictably, the trout population explosion has attracted growing numbers of driftboat anglers, each of whom is searching for a trout of legendary proportions.

To Boname, co-owner of the Platte River Fly Shop in Casper, that quintessential trout is Walter.

"Two years ago on the Fourth of July, we were the only boat on the river," Boname said as he watched a flotilla of driftboats parade downstream from the Gray Reef Access Area. "A lot has changed in two years."

Indeed it has. Four years ago, after years of negotiations and study, the Wyoming Fly Casters, a determined conservation group of only 150 members, prevailed upon the U.S. Bureau of Reclamation to release heavy flushing flows from Alcova Dam upstream.

To achieve the cleanup flows, the Wyoming ...

from generators at Alcova would be a worthwhile sacrifice.

"BoRec is coming around," said Greg Mueller, a river guide for the Platte River Fly Shop, (307) 237-5997. "They realize the recreational value."

Now, every March and October before rainbow and brown trout spawn, the river rises briefly from 500 cubic feet per second to 4,000 cfs. As a result of the scrubbing, aquatic insect populations have recovered and trout eggs survive and hatch. Once the stretch was heavily dependent on stocking. Now more than half of its trout are reproduced naturally.

Shop owner Ron Dutton says about 80 percent of trout in the river are rainbows, 5 to 10 percent are cutthroats and the rest are browns. Based on Game and Fish Department studies, he figures the catchable-sized trout population at 4,000 per mile in the upper reaches below Gray Reef and almost that many downstream in the Lusby to Government Bridge stretch.

"Most people are going to catch trout in the 2-to 4-pound range, and those who know how have a chance at catching a fish over 10 pounds," Dutton said. "The biggest rainbow we've seen was 29½ inches long and 25½ inches around. The Game and Fish Department estimated it weighed 18 pounds."

Predictably, the most productive stretch is where most of the wild trout reproduce, the upper 9 miles from Gray Reef Dam — an afterbay of Alcova Reservoir, to Lusby Access Area. Boname and other anglers frequently and favorably compare the stretch with the famed Miracle Mile, 24 miles upstream on the North Platte River.

wasn't especially forthcoming, but the comparison seemed more than fitting. R... trout, many of them suitable for naming, stacked by the dozens in choice prespawn... locations. Boname drifted by, wisely cho... not to harass those important spawners ... fly and hook.

Elsewhere, a few trout launched at a p... streamer of his own design, a brown Mol... Wooly Bugger with copper conehead, kn... locally as a Bite Me Bugger. But the wa... proved cool and the season early for stre...

Better results followed with a red San... worm drifted deep in the river's currents... size 20 olive Palomino Midge also produc... several takes, including one from a brute... inch male rainbow in gorgeous scarlet sp... colors.

Downstream from Gray Reef, the Nor... te's chief fish food is craneflies, which are... ed with a fly known as a Vanilla Bugger; c... and crayfish. Boname said the river's best... fishing arrives evenings in July and Augu... hatches of yellow Sally stoneflies, caddis, ... Trico mayflies. Large Halfback nymphs al... tate stoneflies and crayfish, and soon a bl... winged olive mayfly hatch will begin.

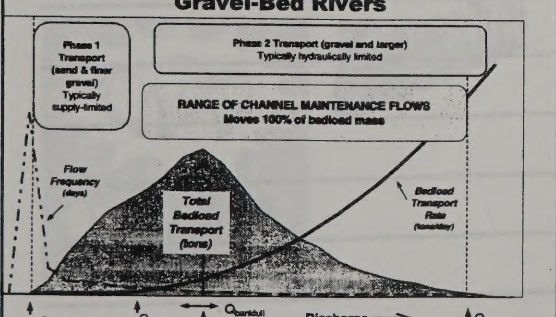
Conservative angling regulations are ... place to ensure this premier stretch hol... the gains it has made: flies and lures onl... Gray Reef Dam downstream to Lusby, ... daily and possession limit of just one tr... inches or longer.

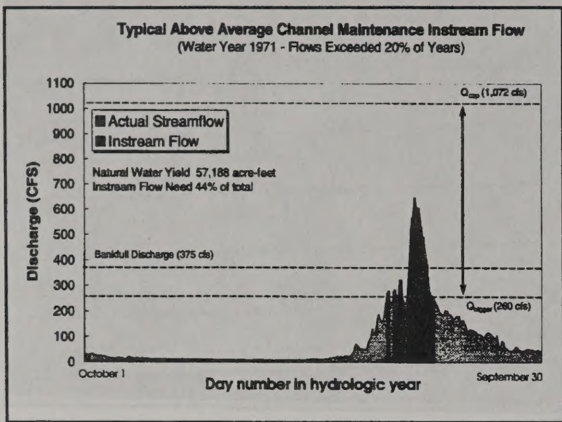
That won't protect Walter entirely. B... should give anglers pause to remember ... honor the hard work that resulted in a ... flush with fish.

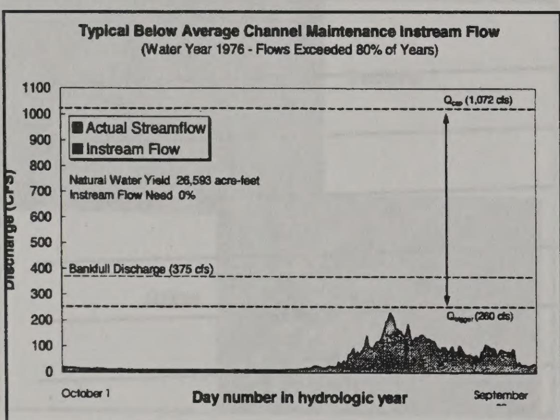
Channel Maintenance

- Range of higher flows ($<Q_{F10}$)
- Gravel bed rivers (unregulated)
- Maintain physical features and processes
  - Bedload transport
  - Channel morphology/geometry
- USDA Forest Service (*See Schmidt and Potyondy, 2001 Handout*)

General Model of Sediment Transport Processes for Channel Maintenance in Gravel-Bed Rivers







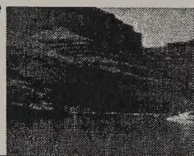
Riparian Restoration

Owens River, CA (See Hill and Platts, 1998 Handout)

- **Passive restoration**
- **Pulse and base flows**
- **Improved aquatic habitat resulted**

"Mimicry" of Natural Hydrograph
San Juan River

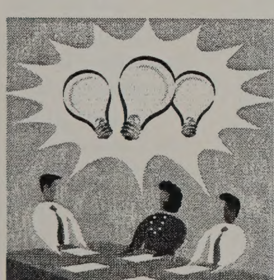
- Mimicry of historic flow variability
- Target species, CPM & RBS
- Based on Q/geomorph/habitat
- Recognizes water use
- Extensive monitoring



(See Holden, 1999 Handout)

SJR Flow Recommendations

Flow (cfs)	Duration (days)	Frequency (years)	Purpose
>10,000	≥5	20%	Out of bank Channel diversity
>8000	10	33%	Bankfull Build cobble bars
>5000	21	50%	Clean backwaters
>2500	10	80%	Clean cobble bars
500	-	-	Baseflow



Discussion

Day 2
The Basic Ingredients

- Instream flow – an issue that has changed the West
- Exploring flow as a habitat factor
- Overview of instream flow methods
- Workshop on developing instream flow recommendations

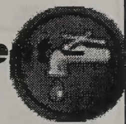
Afternoon Workshop

Developing Instream Flow Recommendations

- WinXSPro
- RHABSIM
- Designing mitigative flushing flow regimes
  - Deschutes Creek Case Study

- Stage gradient (+1%)

Day 2
The Basic Ingredient: WATER

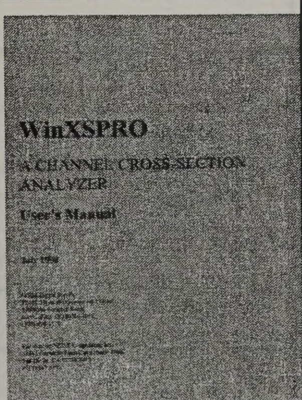


- Instream flow – an issue that has changed the West
- Exploring flow as a limiting factor
- Overview of instream flow methods
- Workshop on developing instream flow recommendations

Afternoon Workshop
Developing Instream Flow Recommendations

- WinXSPro
- RHABSIM
- Designing mitigative flushing flow regime
  - Deadman Creek Case Study

- Interactive Software
- Models single stream channel cross sections
- Geometry, hydraulics and sediment transport
- Steep gradient (>1%)
- USDA Forest Service and WEST



WinXSPRO

A CHANNEL CROSS-SECTION ANALYZER

User's Manual

WinXSPRO Applications

- Channel design
- Riparian restoration
- Instream structures
- Fish habitat evaluation
- Instream flow analyses

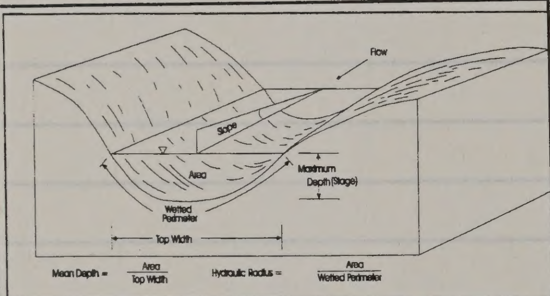
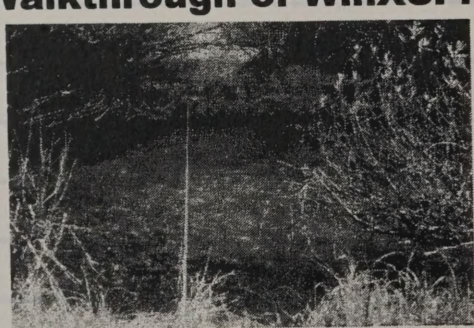
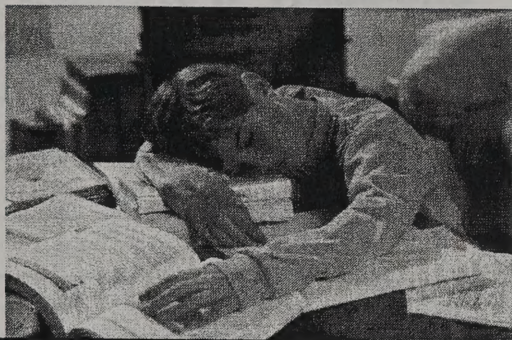


Figure 2.1. Definition diagram for hydraulic parameters. USDA and WEST 1998

Walkthrough of WinXSPro



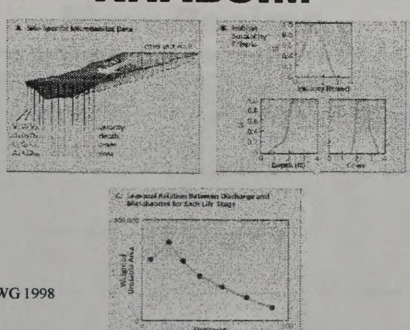
In-Class Problem #7



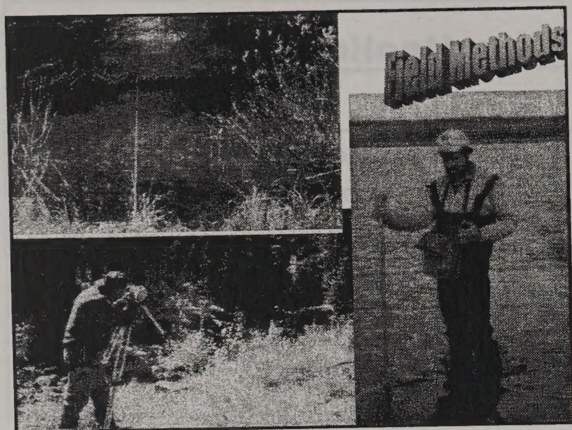
Problem steps

- Load program
- Input field data
- Run program
- Complete analysis
- Compare and discuss results

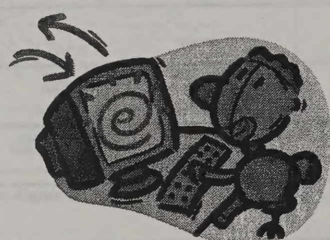
RHABSIM



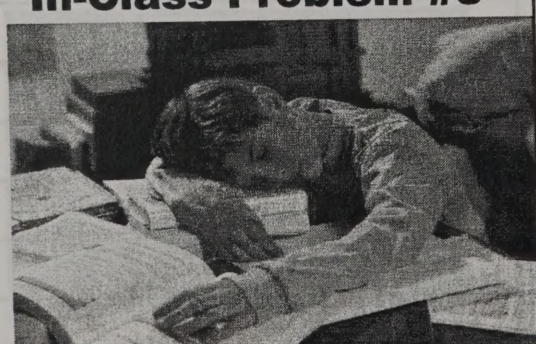
FISRWG 1998



RHABSIM
Walk through



In-Class Problem #8

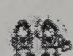


Using RHABSIM to Evaluate IF Trade-offs

- **Information provided**
  - WUA plots for 3 salmonid species and life stages
  - WUA data tables
  - Mean monthly hydrograph plot
  - Flow duration table

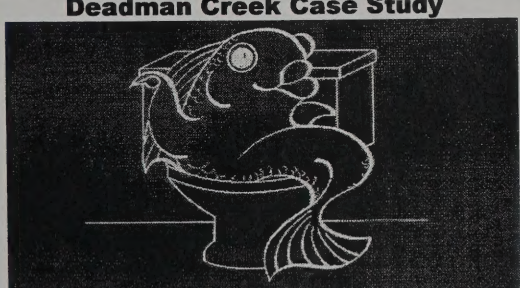
Using RHABSIM to Evaluate IF Trade-offs

- **Information provided**
- **Based on information**
  - Develop periodicity chart
  - Determine optimum flows
  - Incorporate flows into periodicity chart
  - Evaluate instream flow trade-offs by month
  - Compare monthly instream flows to historic records
  - Recommend an instream flow for each month
- **Compare and discuss results**



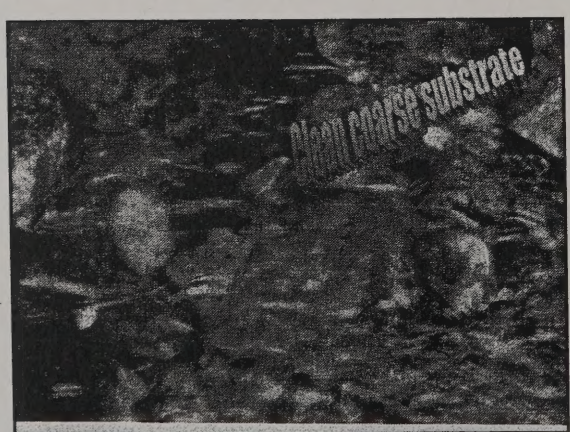
Mitigative Flushing Flow Regime

Deadman Creek Case Study

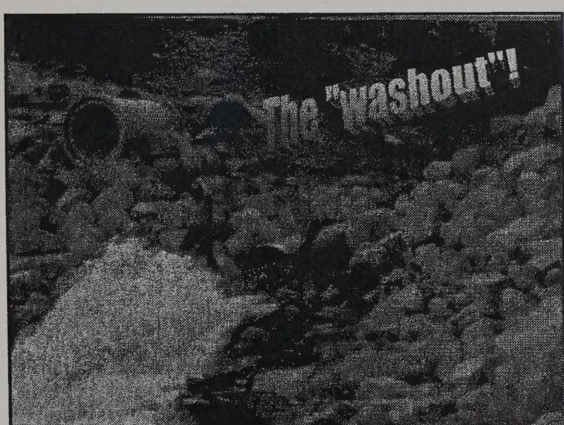


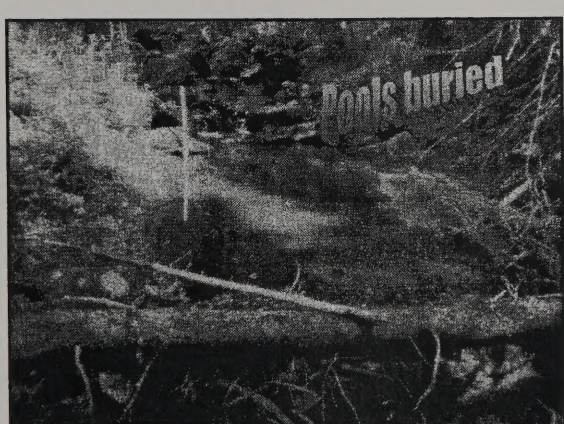

Target Species
River Cutthroat Trout

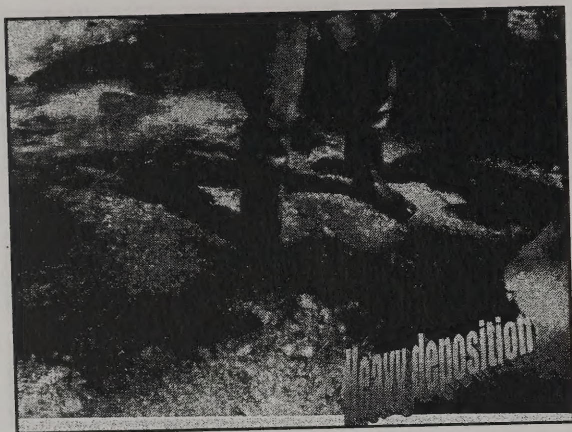

Deadman Creek

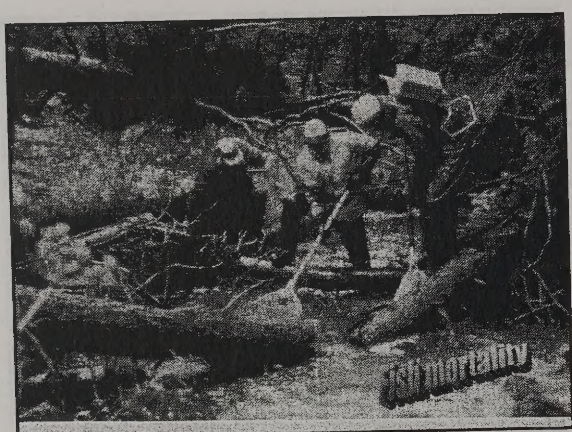

Clean coarse substrate


Log step pools


The "washout"!


Pools buried





Q_{FF} Approach

I. Quantify the problem
II. Select "critical" reach
III. Establish "target"
IV. Develop sediment transport relations
V. Determine magnitude/duration of Q_{FF}
VI. Implement and evaluate

Q_{FF} Approach

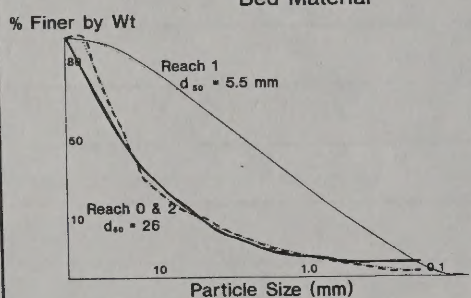
- **Quantifying the problem**
  - **Sediment quantity**
    - deposition depth, lbs/ft², tons
  - **Substrate quality**
    - d_{50}, % fines

Q_{FF} Approach

- **Quantify the problem**
- **Select "critical" reach**
  - Key habitats
  - Deposition characteristics
  - Sediment transport capability
    - "Stream Power-Q_W relations

Deadman Creek - 1987

Bed Material



DEADMAN CREEK
SEDIMENT STORAGE
1987

LOCATION (reach)	STORAGE (lbs/sq ft)
#0	18.2
#1	critical reach -> 56.1
#2	18.2

Natural Pool Storage $\doteq$ 30 lbs/ft² = TARGET

Quantity to be Flushed = 56-30

$\doteq$ 26 lbs/ft²

STREAM POWER

"A measure of sediment transport capability"

$$P = S_w \bar{D} \bar{V} S$$

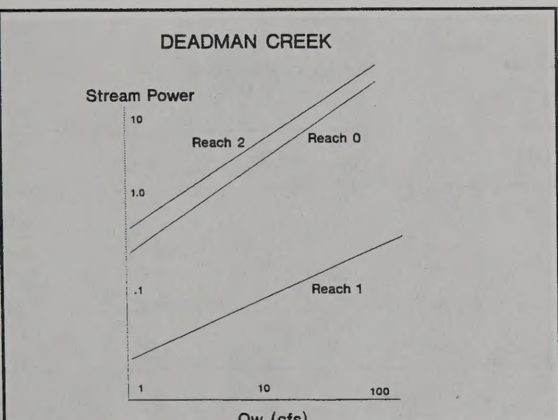
where;

S_w = sp. weight of H20

$\bar{D}$ = mean depth

$\bar{V}$ = mean velocity

S = slope



Q_{FF} Approach

- **Quantify the problem**
- **Select "critical" reach**
- **Establish "target"**
  - Reduction in sediment storage
  - Improvement in substrate quality

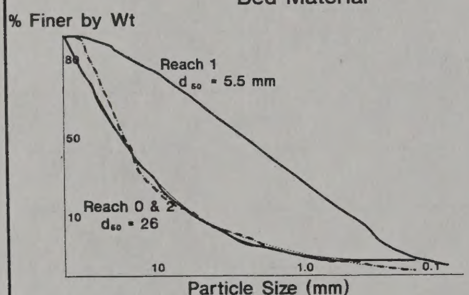
DEADMAN CREEK
SEDIMENT STORAGE
1987

LOCATION (reach)		STORAGE (lbs/sq ft)
#0		18.2
#1	critical reach →	56.1
#2		18.2

Natural Pool Storage ≐ 30 lbs/ft^2 = TARGET

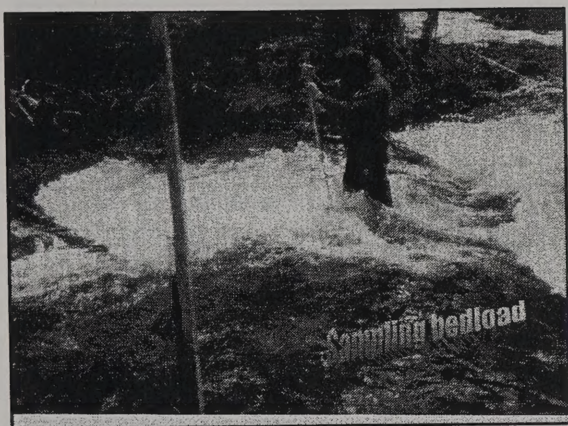
Quantity to be Flushed = 56-30
≐ 26 lbs/ft^2

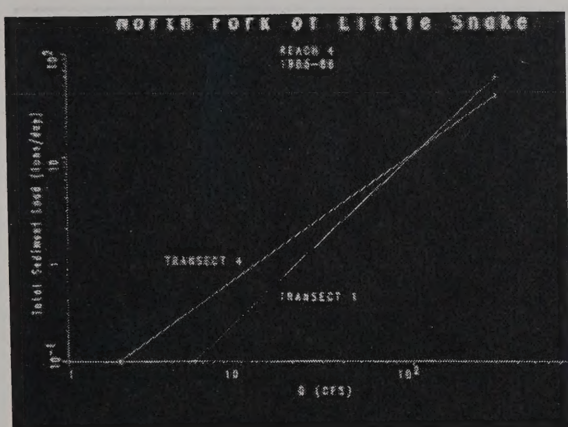
Deadman Creek - 1987
Bed Material



Q_{FF} Approach

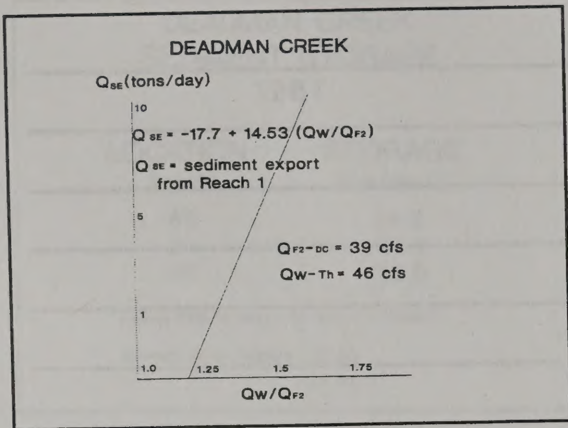
- ➢ **Quantify the problem**
- ➢ **Select "critical" reach**
- ➢ **Establish "target"**
- ➢ **Develop sediment transport relations**
  - ➢Data sources
    - ➢Field sampling
    - ➢Transport models
    - ➢Similar streams
  - ➢Sediment "import-export" from "critical" reach
  - ➢Defining "threshold" of flushing flow





Q_{FF} Approach

- **Quantify the problem**
- **Select "critical" reach**
- **Establish "target"**
- **Develop sediment transport relations**
- **Determine magnitude/duration of Q_{FF}**
  - Net export rate (Q_{SE}) from "critical" reach
  - Relate Q_{SE} to "target"



FLUSHING FLOW DURATION

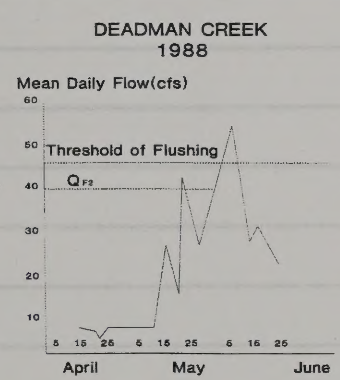
Q (cfs)	$Qw/Q_{\boxed{F2}}$	Q_{SE} T/D	DAYS
48	1.23	0.18	18
50	1.28	0.93	3.5
55	1.41	2.79	1.2
60	1.54	4.65	0.7

DEADMAN CREEK RECOMMENDATIONS

Q (cfs)	Duration (days)	Days Q>= (1988)
50	3.5	2.8
55	1.2	1.5
60	0.7	0.7

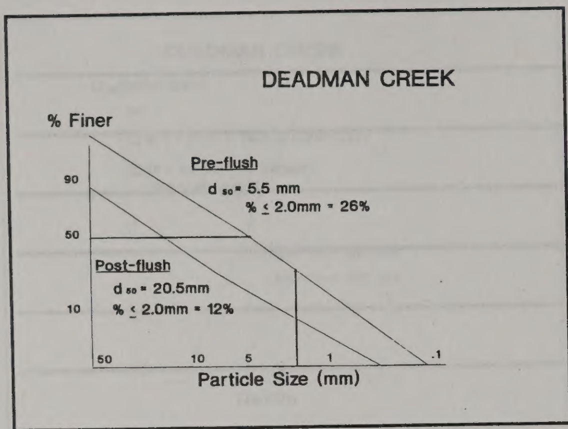
Q_{FF} Approach

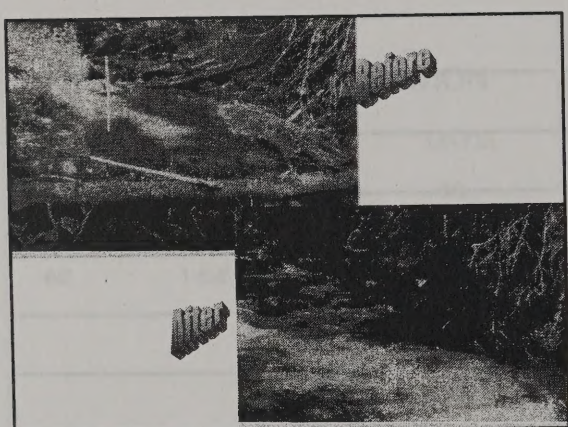
- Quantify the problem
- Select "critical" reach
- Establish "target"
- Develop sediment transport relations
- Determine magnitude/duration of Q_{FF}
- Implement and evaluate
  - Negotiation
  - Monitoring



DEADMAN CREEK EVALUATION

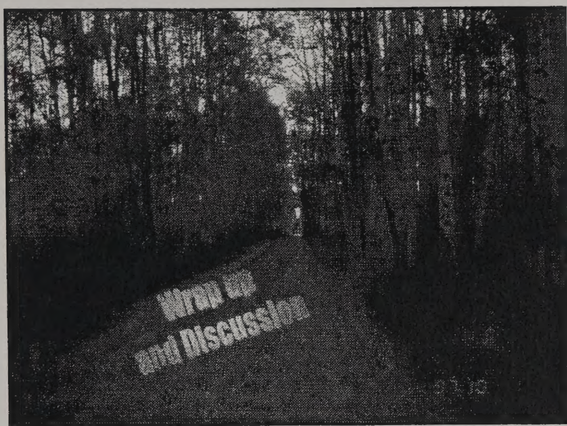
DATE	LBS/SQ FT	$\boxed{d_{50}}$ (mm)
8/14/87	56.1	5.5
6/29/88	36.3	20.5

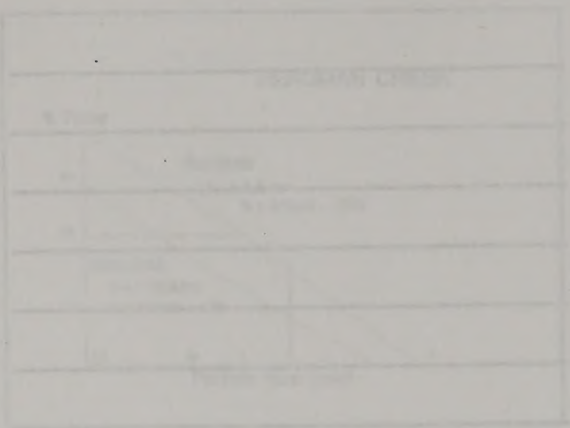


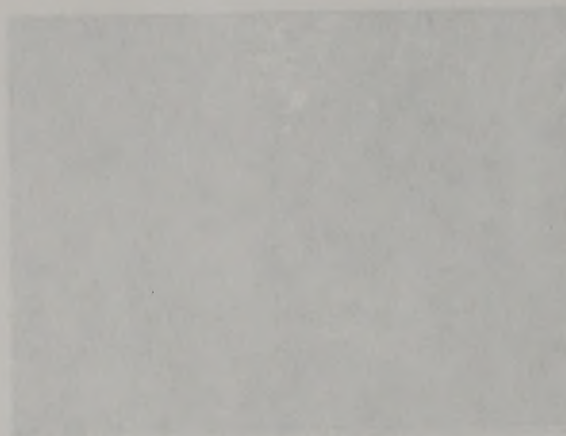


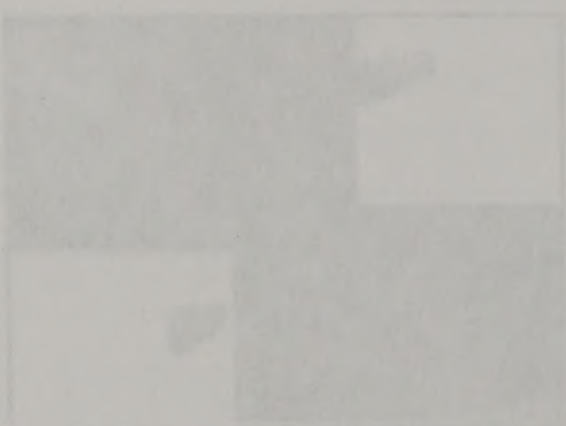
Q_{FF} Approach

- Quantify the problem
- Select "critical" reach
- Establish "target"
- Develop sediment transport relations
- Determine magnitude/duration of Q_{FF}
- Implement and evaluate


Wrap up
and Discussion







Q_{eff} Approach

- Quantify the problem
- Select "critical" reach
- Establish "target"
- Develop sediment transport relations
- Determine magnitude/duration of Q_{eff}
- Implement and evaluate

Day 3
Fish Passage

BLM TRAINING COURSE No. 7000-12
AQUATIC HABITAT RESTORATION & ENHANCEMENT
August 5 - 9, 2002
Albuquerque, NM

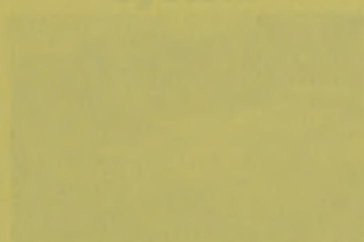
DAY THREE: Habitat Restoration Analysis & Design - FISH PASSAGE & FIELD TRIP

- Review and clean-up from Day Two (15 minutes)
  WORKSHOP ON FISH PASSAGE
- Re-connecting the river system, an escalating issue! (15 minutes)
  - ✓Importance of assuring passage for fisheries
  - ✓Common types of barriers
    - ☺Natural
    - ☺Man-made
- Barrier analysis; Can they make it? (1 hour, 15 minutes)
  - ✓Evaluating potential barriers
    - ☺Barrier geometry
    - ☺Stream hydrology
    - ☺Barrier hydraulics
    - ☺Entrance, passage zone and exit conditions
  - ✓Fish capabilities
    - ☺Swimming speed and performance
    - ☺Leaping capabilities
  - ✓In-class Problem #9- Barrier analysis for cutthroat trout
- Fish passage solutions (2 hours)
  - ✓Channel conditions - Putting your habitat survey to work!
    - ☺Identifying your passage bottlenecks
    - ☺Douglas Creek puzzle
    - ☺South Fork of Coeur d' Alene River examples
    - ☺Some solutions
  - ✓Fishway designs - engineered structures at "major" facilities
    - ☺General layout of a fishway site
    - ☺Types of fishway designs
  - ✓Culvert analysis and design - Introduction to FishXing software program
    - ☺Is your culvert a passage problem?
    - ☺Mini-lectures on culvert hydraulics
    - ☺Walk-through of FishXing software (each participant will get copy)
    - ☺In-class Problem #10- Using FishXing to re-design the upper Douglas Ck culvert
- **Lunch Break**
- **AFTERNOON FIELD TRIP (1:00 - 6:00PM)**
  - ✓Tour of MRG, Albuquerque to San Acacia
  - ✓Tour stops will highlight planned and ongoing river restoration activities including re-establishment of native riparian vegetation, RGSM habitat enhancement, fish passage design options, and water conservation/management strategies
  - ✓Guest speakers from BOR, MRGCD, and NMSU

Day 3
FISH PASSAGE

- Re-connecting the river system
- Barrier analysis
- Fish passage solutions
- Field trip

Re-connecting the River System

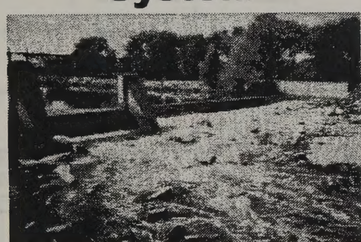


An escalating issue!

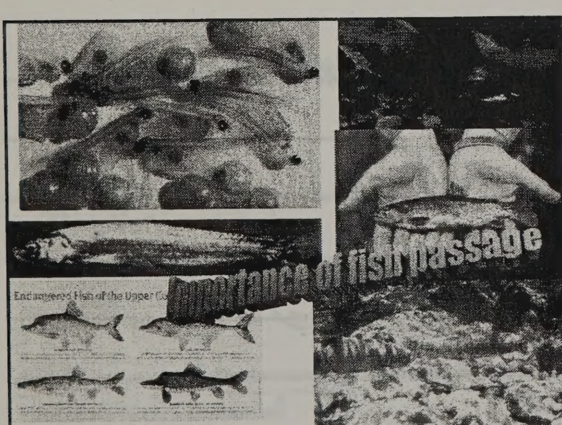
Day 3
FISH PASSAGE

- Re-connecting the river system
- Barrier analysis
- Fish passage solutions
- Field trip

Re-connecting the River System

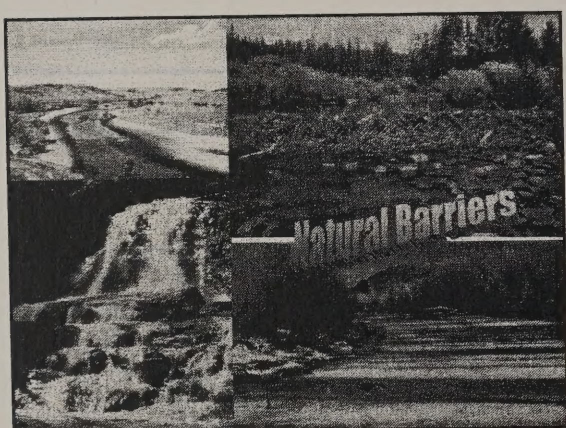


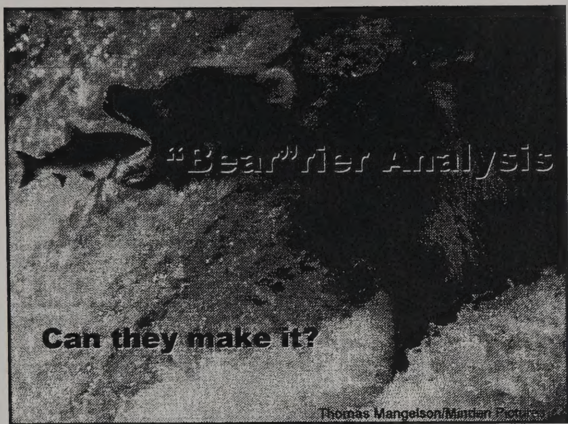
An escalating issue!

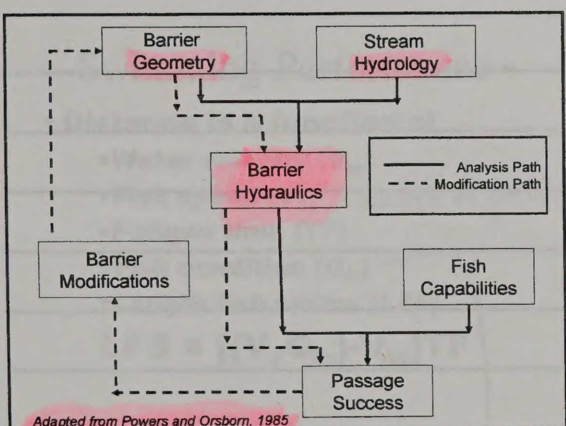


Barriers to Fish Migration

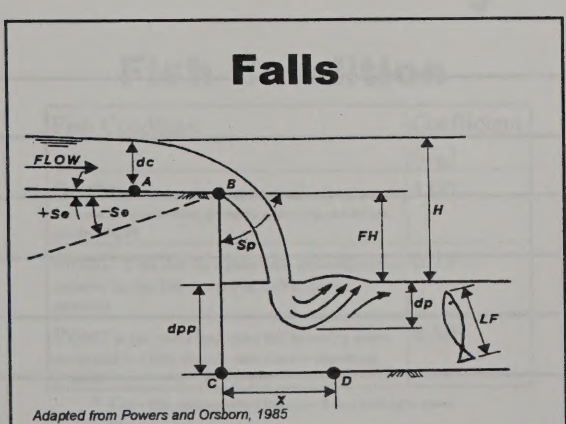
- Natural
- Man-made



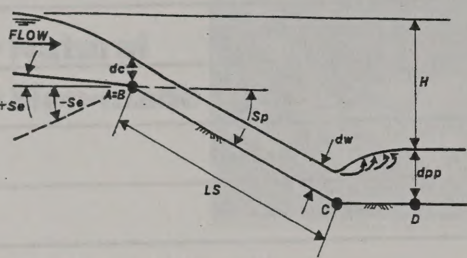




← excellent citation to have in your library



Chute

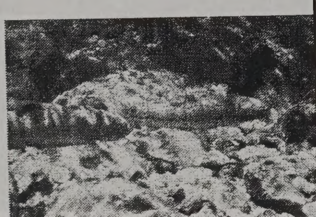


Adapted from Powers and Orsborn, 1985

a culvert is a chute

Fish Capabilities

- Swimming speed
- Swimming performance
- Leaping capabilities



Fish Capabilities

- Swimming speed
  - Sustained
    - no fatigue; normal functions
  - Prolonged
    - 15 sec to 200 minutes; result in fatigue
  - Burst
    - fatigue in 15 seconds or less

Fish Speeds

(ft/sec)

Species	Sustained	Prolonged	Burst
Steelhead	0-4.6	4.6-13.7	13.7-26.5
Chinook	0-3.4	3.4-10.8	10.8-22.4
Coho	0-3.4	3.4-10.6	10.6-21.5
Sockeye	0-3.2	3.2-10.2	10.2-20.6
Pink & Chum	0-2.6	2.6-7.7	7.7-15.0
Cutthroat Trout	0-2.5	2.5-6.0	6.0-14.0
Brown Trout	0-2.5	2.5-7.0	7.0-13.0
RGSM	??	??	??

Bell 1984 ??=research underway

lots of data on the salmonids

1 ft/sec / inch of fish length = rule of thumb for fish speed.

Swimming Performance

- **Distance is a function of**
  - **Water velocity (V_w)**
  - **Fish speed (V_F)** - burst or prolonged speed
  - **Fatigue time (TF)**
  - **Fish condition (C_{fc})**
  - **Length fish swims (LFS)**

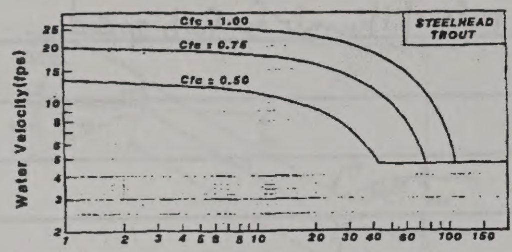
$$LFS = [(V_F C_{fc})-V_W]TF$$

Fish Condition

Fish Condition	Coefficient (C_{fc})
Bright: fresh out of salt water or still a long distance from spawning grounds; spawning colors not yet developed	1.00
Good: in the river for a short time; spawning colors apparent but not fully developed; still migrating upstream	0.75
Poor: in the river a long time; full spawning colors developed and fully mature; very close to spawning grounds	0.50[a]

[a] C_{fc} = 0.50, corresponds to the upper limit of prolonged speed

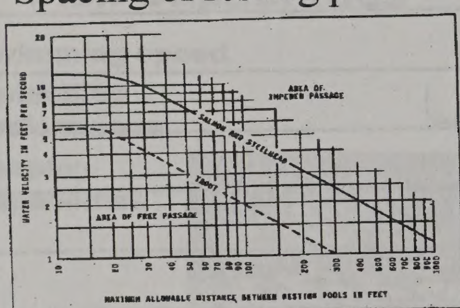
Example of LFS



From Powers and Orsborn, 1985

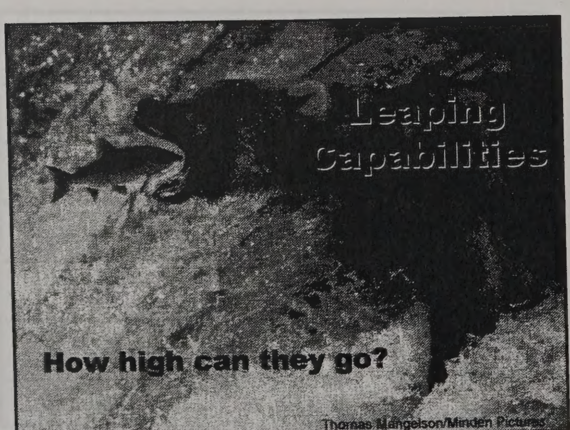
LFS = length fish swims

Spacing of resting pools

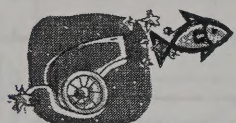


From Evans and Johnston, 1980

trout and salman + steelhead
Research was on adults.
Need to be careful when
considering juveniles



Leaping Capabilities



Analysis based on Projectile motion

HL = (tanθL) XL – [G(XL)²/2 (VFcosθL)²]

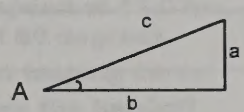
Solve for HL by varying XL

HL – leap height

XL = Horizontal length of leap

$$HL = (\tan\theta L)\, XL - [G(XL)^2/2\,(VF\cos\theta L)^2]$$

- HL = Leap height (a)
- θL = angle of leap (A)
- XL = Horizontal length of leap (b)
- G = 32.2 ft/sec²
- VF = Burst speed



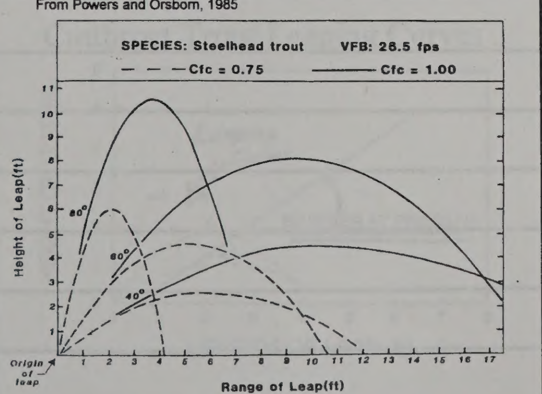
For Angle A:
tanA=a/b
sinA =a/c
cosA =b/c

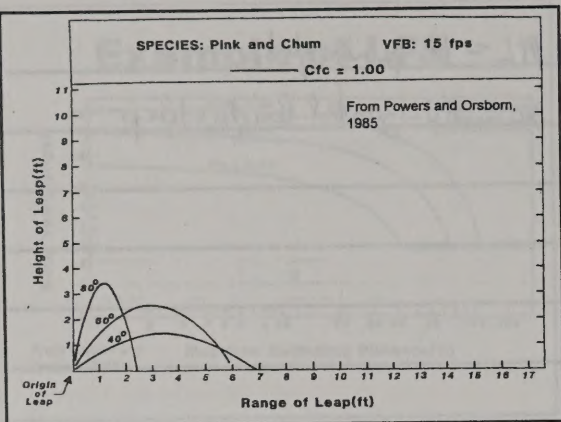
HL

θL = 60

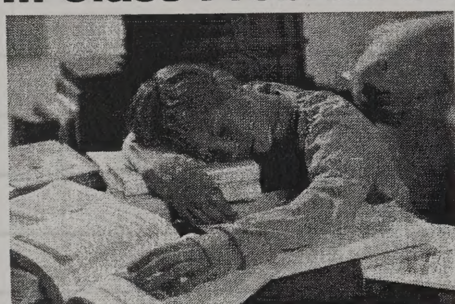
VF = 13 fps

From Powers and Orsborn, 1985

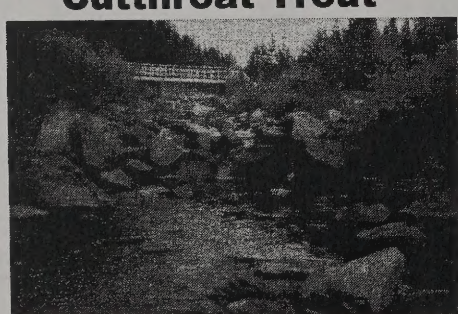


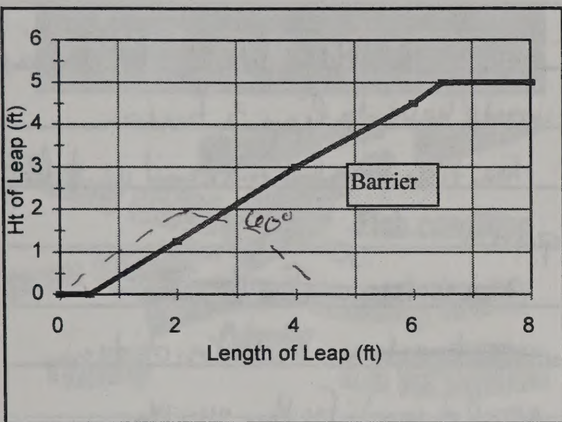


In-Class Problem #9



Barrier Analysis for Cutthroat Trout



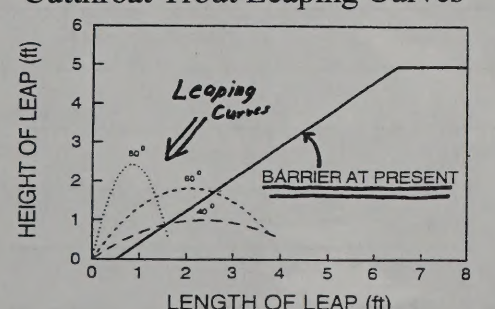


can only leap 2 ft high at 60°

Problem

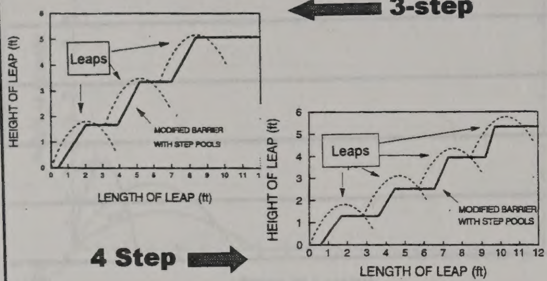
- Assume a burst speed of 13.0 fps, and leap angle of 60 degrees
- Plot the cutthroat leaping curve
- Will cutthroat pass the barrier?
- If not, how would you modify the barrier?

Cutthroat Trout Leaping Curves



Barrier Modifications
Cutthroat

3-step



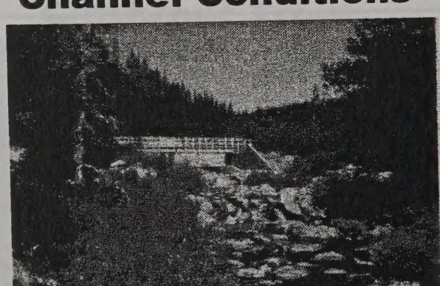
4 Step

Survival of the fitest - best leapers would have to leap 3 times.
More fish would make it w/ 4 leaping pools.
Fish Condition would modify the curve.

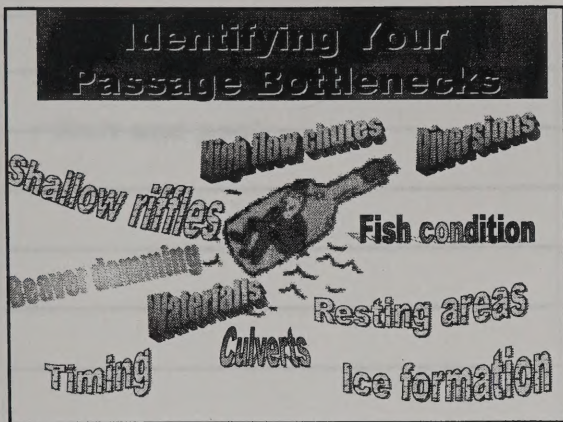
Fish Passage Solutions

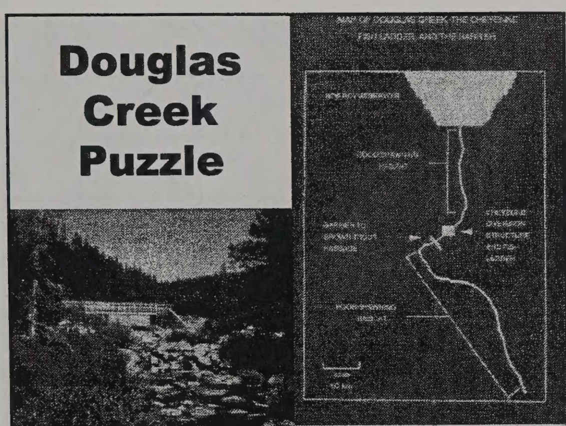
- Channel Conditions
- Fishway designs
- Culvert analysis

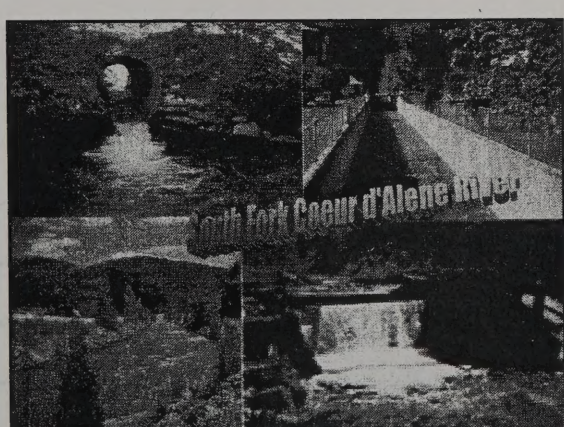
Channel Conditions



Putting your habitat survey to work!


Identifying Your Passage Bottlenecks
High flow chutes
Diversions
Shallow riffles
Fish condition
Beaver damming
Waterfalls
Resting areas
Culverts
Timing
Ice formation

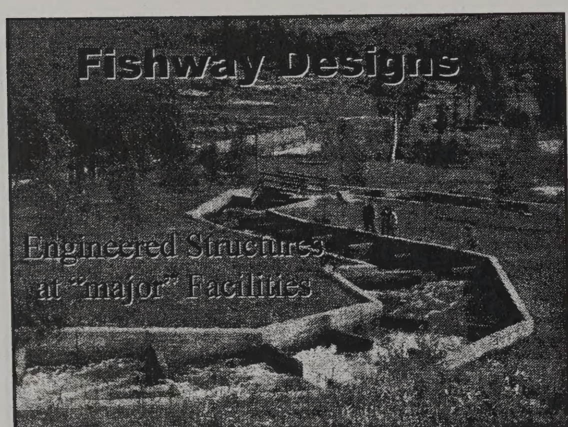

Douglas Creek Puzzle

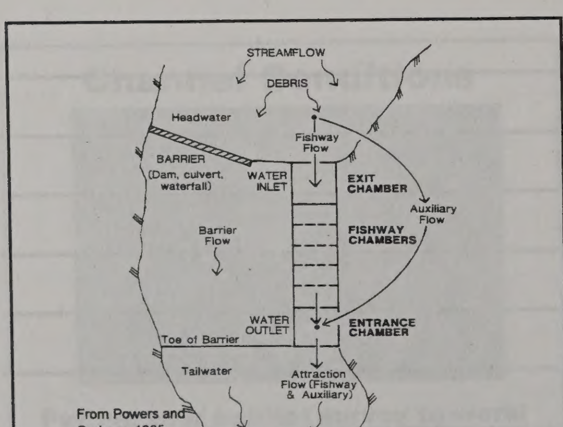

South Fork Coeur d'Alene River

Some Solutions

- **Stream flow management**
- **Minor channel modifications**
- **Structural channel management**

Movement was distracting

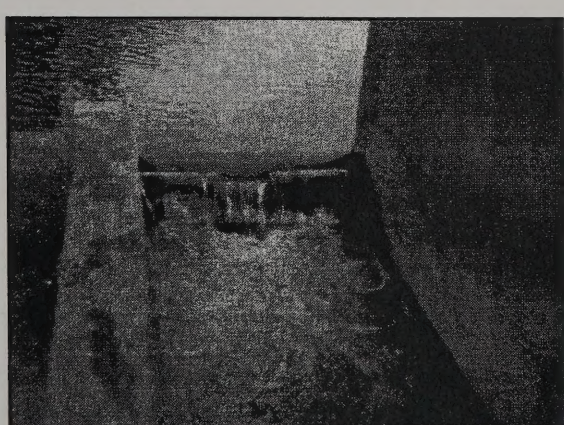


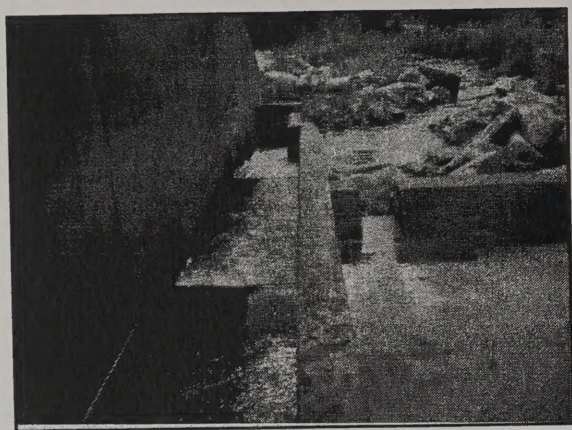


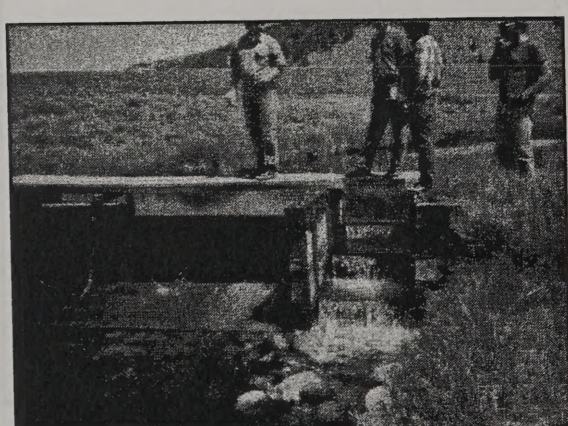
From Powers and Orsborn 1985

Types of Fishways

- Weir and pool

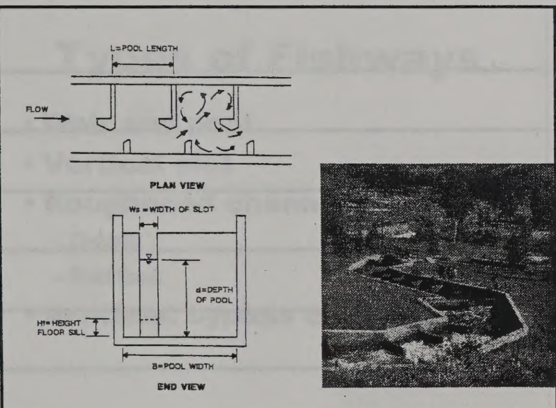






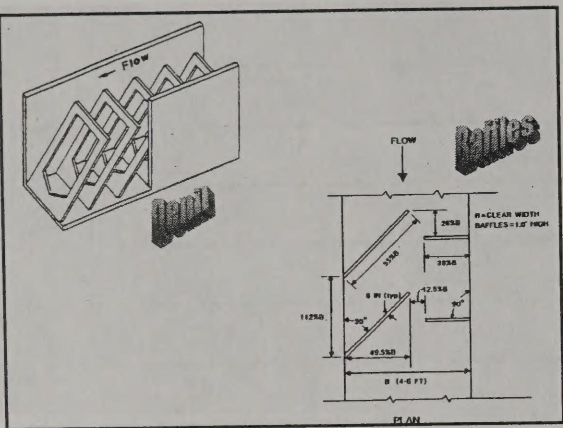
Types of Fishways

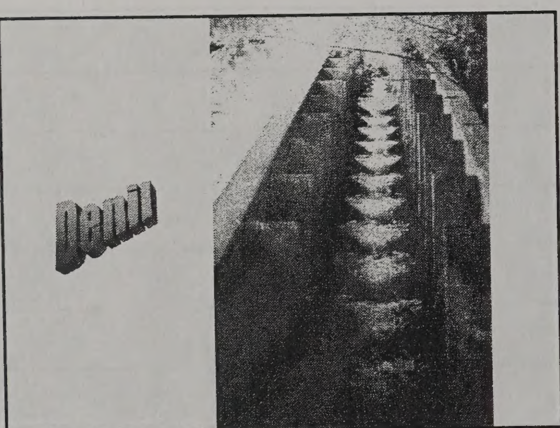
- Weir and pool
- Vertical slot

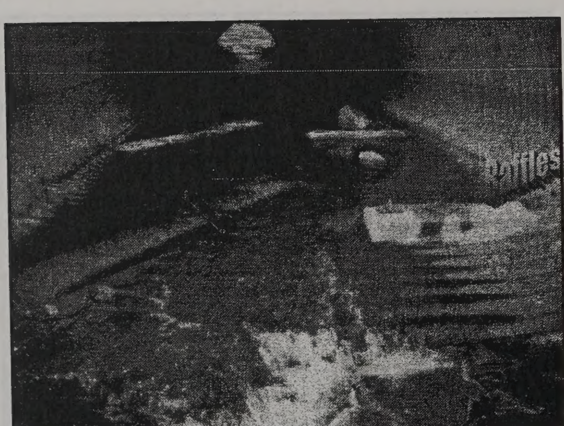


Types of Fishways

- Weir and pool
- Vertical slot
- Roughened channel
  - Denil
  - Baffles


Flow
Denil
Baffles
FLOW
42.5%B
49.5%B
112%B
30°
90°
B (4-6 FT)
PLAN

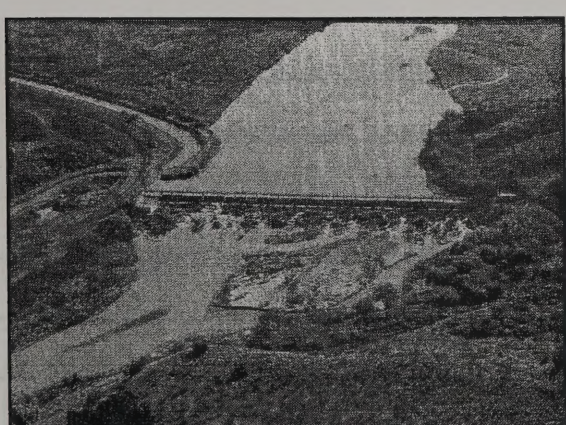

Denil


Baffles

230
11|25
22
30

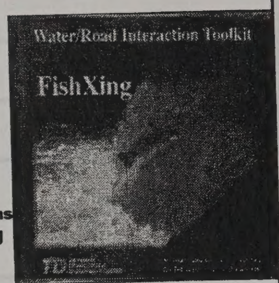
Types of Fishways

- Weir and pool
- Vertical slot
- Roughened channel
  - Denil
  - Baffles
- Artificial bypass channels



FishXing

- Pass out software
- Install FishXing
- Is your culvert a problem?
  - Good, Bad and Ugly
- Sing-a-long
- Mini-lectures
  - Hydrology
  - Hydraulics
  - Tailwater Considerations
- Walk-through FishXing
- In-class problem

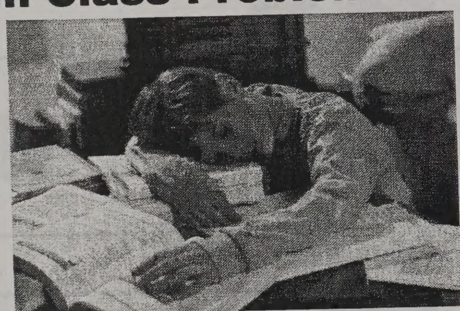


need to break up the lectures by breaks or exercises.

"Manning's Equation" could be more defined

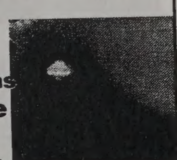
Quick Time - visual is not smooth

In-Class Problem #10

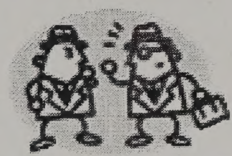


Douglas Creek Culvert Analysis

- Design data
  - 154 ft steel pipe arch (12'10" x 8'4") on 0.8% grade
  - Cutthroat trout
  - Flows 1.6-200 cfs
  - No inlet or outlet problems
- Input data and calculate
- Will cutthroat pass?
- If not, what can you do?
- Compare and discuss results

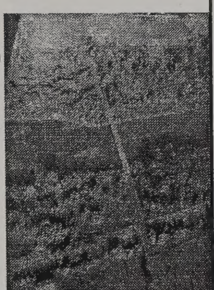


Culvert Design Discussion



Afternoon Fieldtrip 1:00 to ~6:00 PM

- MRG, Albuquerque to San Acacia
- Tour stops
  - Los Lunas
    - RGSM habitat restoration
    - Riparian restoration
  - San Acacia
    - Fish passage planning
    - RGSM ecology
    - Water conservation and management



Invited Speakers

- Mr. Sterling Grogan, MRGCD
- Mr. Chris Gorbach, BOR
- Mr Drew Baird, BOR
- Dr. David Cowley, NMSU

Day 4

Structural Habitat Management

BLM TRAINING COURSE No. 7000-12
AQUATIC HABITAT RESTORATION & ENHANCEMENT
August 5 - 9, 2002
Albuquerque, NM

DAY FOUR: Habitat Restoration & Design - Structural Habitat Management (SHM)

- Review and clean-up from Day 3 (15 minutes)

- Role of SHM in aquatic habitat restoration; Is there one? (45 minutes)
  ✓What is SHM? A definition.
  ✓Some issues regarding SHM!
  ✓When and where might SHM be warranted.

- Planning and implementing an SHM project (45 minutes)
  ✓Some guiding principles
  ✓Overview of steps in the SHM process
  ✓Common habitat deficiencies remedied by SHM

- Coffee Break (15 minutes)

WORKSHOP - "Art and Science of Structural Habitat Management" (6 hours)

- Review of governing physical principles and properties
  ✓Design hydrology, the flows that govern your project
    ☺High flows, the energy needed to create habitats
    ☺Low flows, providing habitat over most of the year
    ☺Intermediate flows, for special habitat needs at specific times
    ☺In-class Problem #11- Determining design flow
  ✓Stream hydraulics, the behavior of flow within the channel boundary
    ☺Ten basic tenets of stream hydraulics from an SHM perspective
    ☺Two Laws of Physics to consider
    ☺Manning's equation and the "ideal" channel
    ☺When and why do stream sediments move?
    ☺In-class Problem #12- Evaluating boulder stability
  ✓Channel morphology, the template for SHM
    ☺Using channel classification as a guide
    ☺Stream Reach Inventory and Channel Stability Evaluation (SRI/CSE)
    ☺In-class Problem #13 - Applying the SRI/CSE to the Santa Fe River
    ☺Comparing reference and test streams to assess condition

- Lunch Break

- Tools of the trade; Design criteria and uses for common structural treatments
  ✓Overpour structures; weirs, check dams, plunges, berms, and sills
    ☺Purposes

☺Design
☺Siting
☺Hydraulic considerations
☺In-class Problem #14 - Evaluating hydraulics of a log overpour

✓Deflectors and constrictors
☺Purposes
☺Design
☺Siting
☺Hydraulic considerations

✓Substrate modifications for rearing and spawning
☺Boulder placements
☺Treatments for spawning substrate development
☺In-class Problem #15 - Using WinXSPRO to evaluate spawning gravel stability

✓Additional treatments for habitat structure and complexity
☺Tree retards or revetments
☺Tree covers
☺Rootwads
☺Half-logs
☺Additional information sources

✓Consideration of "uncertainty" in SHM
☺Why be concerned?
☺Sources of uncertainty
☺Evaluating failure of treatments
☺Factors to consider in assigning risk priority

✓In-class Problem #16 - SHM planning for the Santa Fe River

- Wrap-up of Day Four

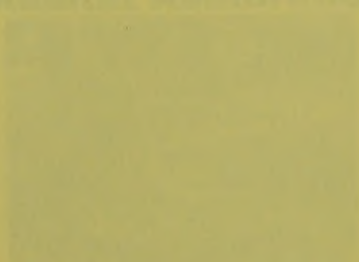
Day 4

Structural Habitat Management (SHM)

Day 4

- Role of SHM in aquatic habitat restorations is there one?
- Planning and implementing SHM projects
- [illegible]
  - [illegible]
  - [illegible]

Role of SHM in Aquatic Habitat Restorations



Is there one?

[illegible]

Day 4

Structural Habitat Management (SHM)

Calvin and Hobbes **by Bill Watterson**

Look! a trickle of water running through the dirt.

I'd say our afternoon just got booked solid.

Day 4

- **Role of SHM in aquatic habitat restoration: Is there one?**
- **Planning and implementing SHM projects**
- **Workshop: "Art and Science of SHM"**
  - Review of governing physical principles and properties
  - Tools of the trade; Design criteria and uses for common structural treatments

Role of SHM in Aquatic Habitat Restoration:

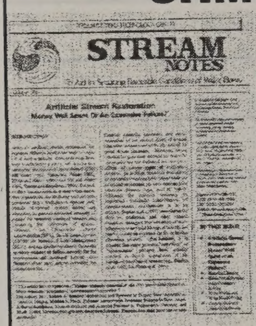
Is there one?

What is SHM?

"Artificial alteration of the channel boundary and associated flow characteristics to restore or enhance aquatic habitat quantity or quality"

Definition created by the course instructor + Jim Fogg.

SHM Issues

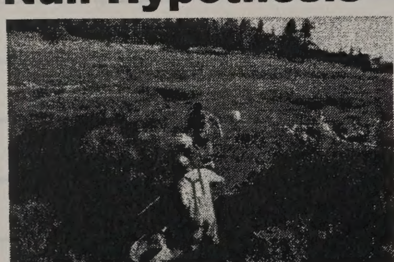


(Handout)

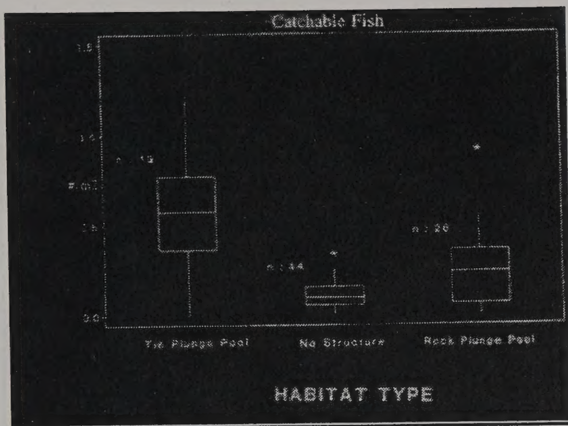
- Treating symptoms or curing disease?
- Viable alternative to passive restoration?
- Cost effective or waste of money?
- Long-term benefits or short-term fix?
- Aesthetically pleasing or artificially engineered?
- Sound management or socio-political scape-goat?
- Scientifically valid or untested hypothesis?

1985 "Artificial Stream Restoration"

Null Hypothesis



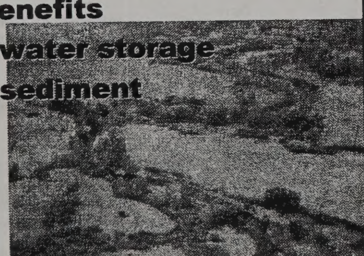
Stream improvement projects have had no effect on fisheries habitats and populations



When and Where is SHM Warranted?

Complement Watershed Based Restoration

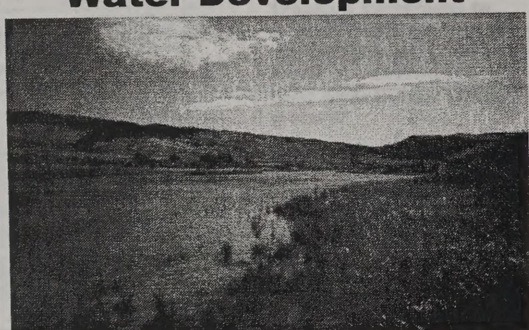
- Provide short-term habitat benefits
- Promote water storage
- Promote sediment storage



Total Reconstruction Not Possible

- Channelization
- Mining/dredging
- Urban areas

Channels Affected by Water Development



Special Situations

- Property protection
- Put and take fisheries
- Handicapped access
- Recreation

Not PC

Planning and Implementing an SHM Project

Guiding Principles

- Learn from nature and anglers
- Don't make it something it can't be
- Focus on limiting factors
- Consider species requirements
- Don't cookbook it!
- Disguise artificiality
- Encourage native vegetation
- Enhance meanders and pool-riffles
- Make sure you have flow!
- Promote water storage – why?
- Integrate with other management
- Follow logical sequence

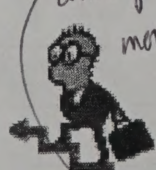
Adapted from Hunt, 1993

from Wisconsin

Steps in SHM Process

- Form inter-disciplinary team
- Establish overall goal
- Examine stream
- Diagnose potential and deficiencies
- Decision: should we proceed?
- Set specific objectives
- Design treatments
- Estimate costs
- Decision: Go or no go?
- Obtain permits
- Develop schedules
- Install treatments
- Evaluate initial effects
- Inspect and evaluate annually
- PERFORM MAINTENANCE

annoying movement



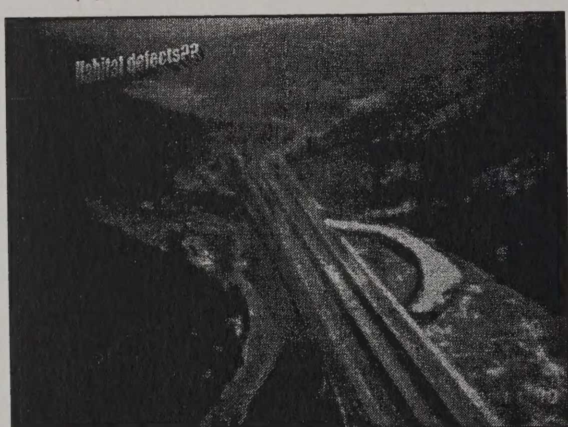
Adapted from Orth and White, 1999

Based on the ~~discussion~~ absence of the value of SHM testing the null hypothesis how valuable is this list.

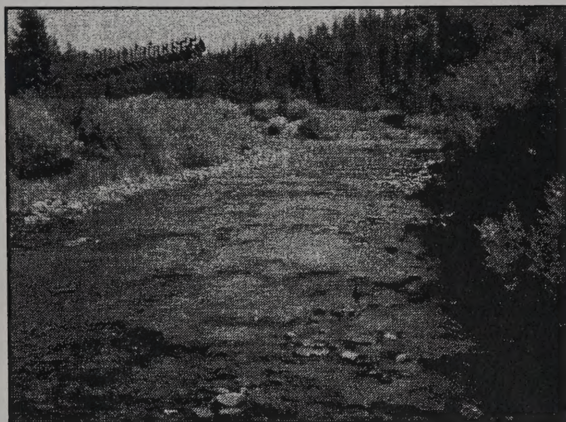
Common Habitat Deficiencies Remedied by SHM

- Homogenous channel form
- Inadequate pool quantity and quality
- Inadequate cover
- Reduced over-winter habitat
- Inadequate spawning habitat
- Inadequate low-velocity habitat
- Excessive substrate embeddedness
- Unstable bed material
- Excessive or inadequate shading
- Unstable, eroding banks

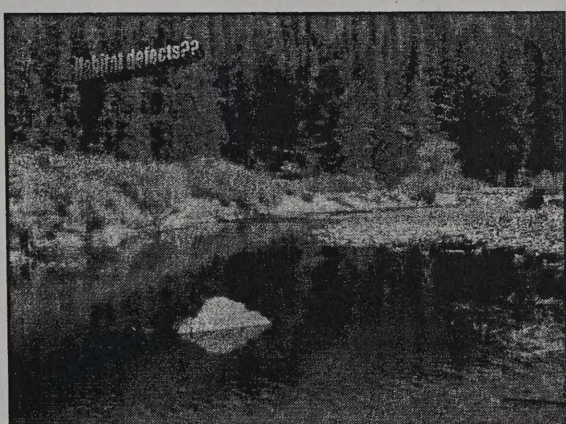
Point made by a student:
Do a cause + effect analysis support the SHM solution



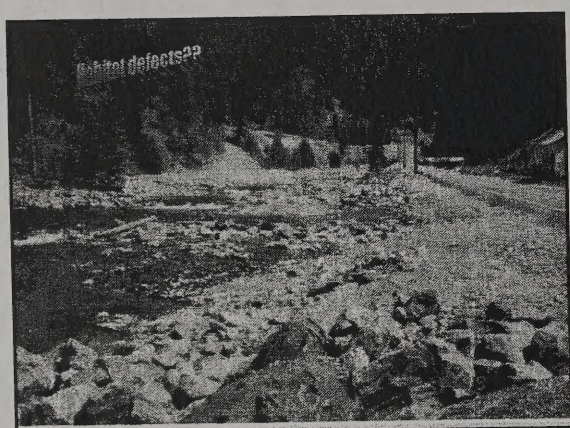
grazing removal may be the solution.

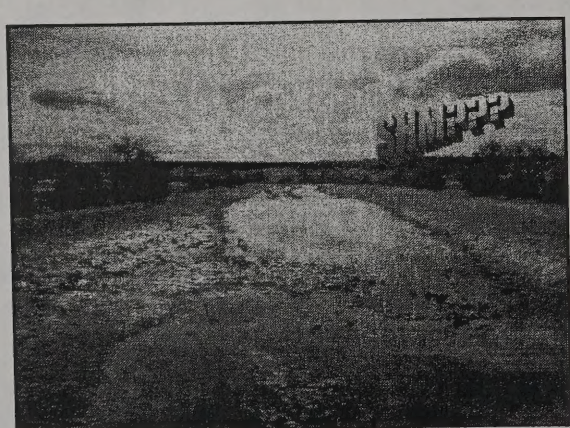


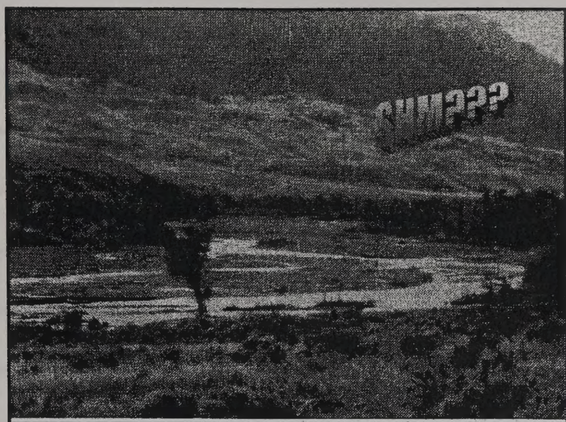
Very homogenous; Lack of pools shallow; not a range of depths to support diff. life stages. Don argued that this is the norm/natural in Alaska so we should do no restoration.

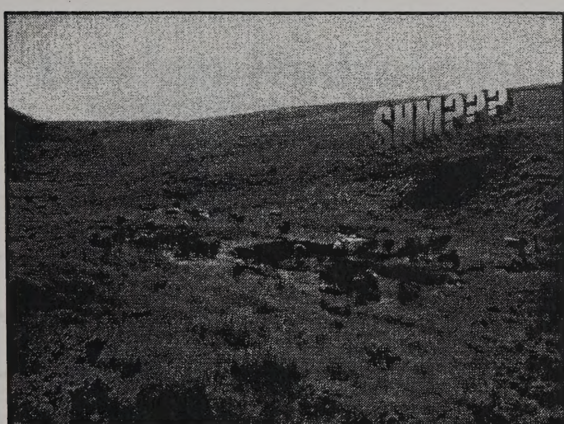


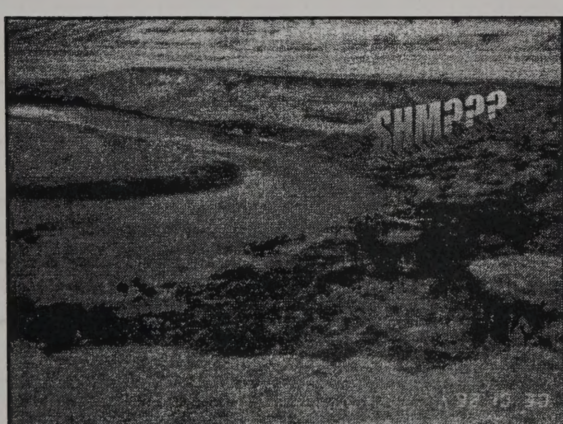

Habitat defects??

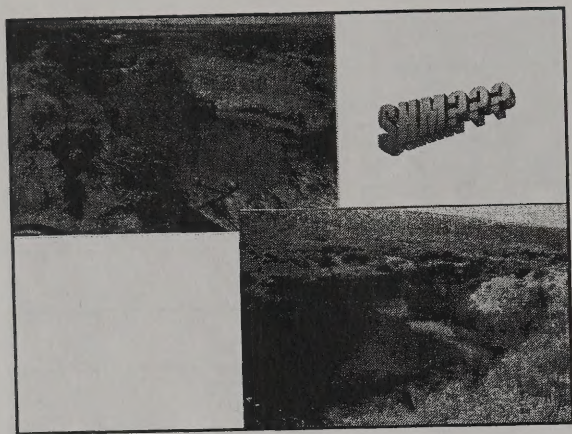

Habitat defects??

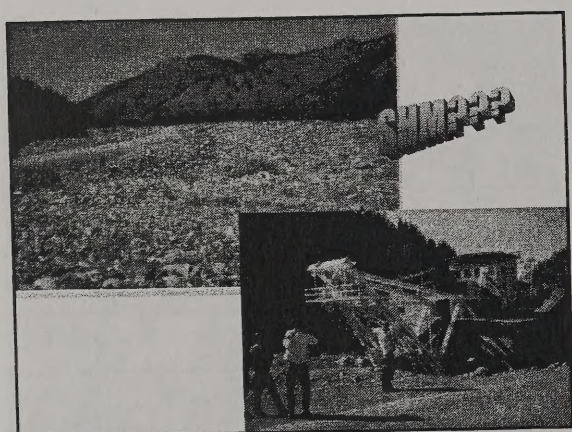


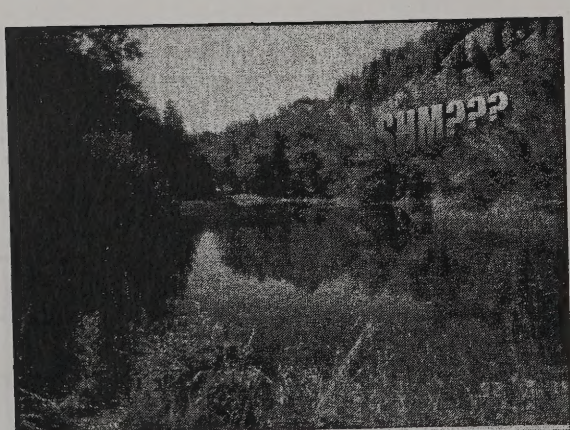

SHM???


SHM???


SHM???

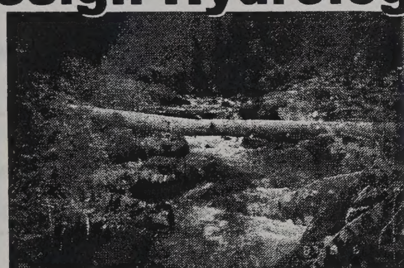

SHM???


SHM???


SHM???

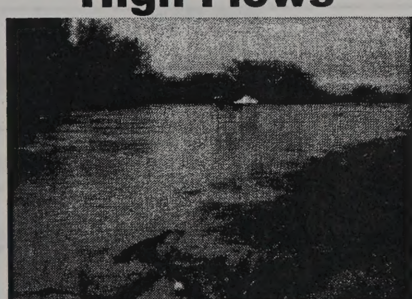
Workshop: Art and Science of SHM

Design Hydrology



The Flows that Control Your Design

High Flows



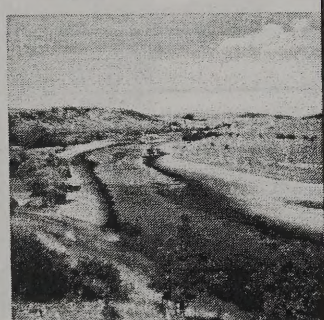
The energy to create habitats

High Flows

- **Importance**
  - Treatment stability
  - Potential channel and out-of-channel damage
  - Scour and deposition processes
- **Common design flows**
  - Bankfull flow
  - Q_{F2}

Low Flows

Habitat maintenance over most of year

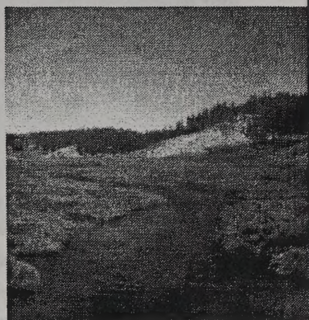


Low Flows

- **Importance**
  - Rearing habitat
  - Temperature regime
  - Reproduction
  - Movement
- **Common design flows**
  - Q_{90} from annual duration series
  - Q_{50} from monthly duration series
  - Q_{7L10}

Intermediate Flows

Special habitat needs at specific times

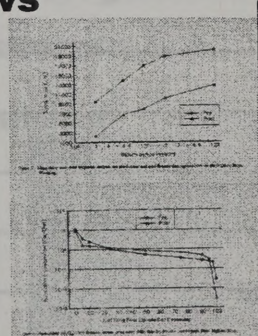


Intermediate Flows

- **Importance**
  - –Reproduction
  - –Movement
- **Common design flow**
  - –Q_{50} for specific month or period

Determining Design Flows

Analysis of existing gage records

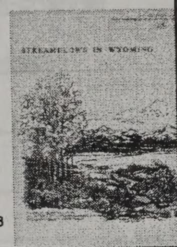


Determining Design Flows

- **Statistical Models**
  - Watershed characteristics

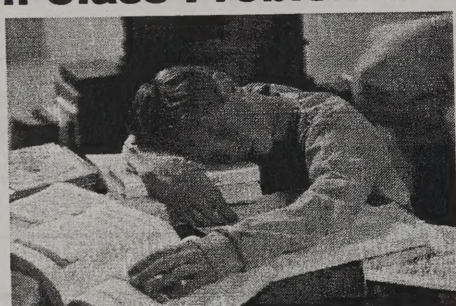
    $Q_{F2}=0.012A^{0.88}(ELEV/1{,}000)^{3.25}$
  - Channel morphology

    $Q_{F2}=1.94\ W^{1.58}$



Lowham 1988

In-Class Problem #11



Problem: Determining Design Flow

- **Data provided for Greybull River, Wyoming**
  - USGS flood frequency analysis
  - Watershed measurements
  - Channel measurements
- **Interpret flow analyses and apply models to:**
  - Estimate high design flow by three methods
  - Compare design flow estimates
- **Discussion**

Stream Hydraulics

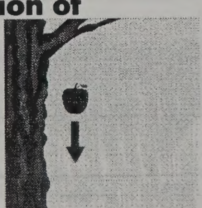
Behavior of the flow within the channel

Ten Basic Tenets of Stream Hydraulics

- Basic laws of physics *do* apply to streams
- Uniform flow is generally bad, non-uniform good
- Smooth, straight channel is bad; roughened, meandering channel good
- Ideal channel for conveying water is not ideal for fish
- Sub-critical flow is generally preferred, but super-critical is also needed
- Both scour and deposition needed for good habitat
- If drag forces exceed resisting forces, something will move
- Flow in natural channels is often too complex to analyze accurately
- Observation is often more valuable than detailed analysis
- Hydraulic uncertainty is always a SHM concern

Two Laws of Physics

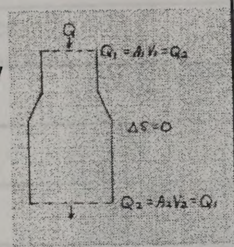
- Law of conservation of mass
- Law of conservation of energy



Law of Conservation of Mass

- **"Mass not created or destroyed"**
- **Basis for Continuity equation**

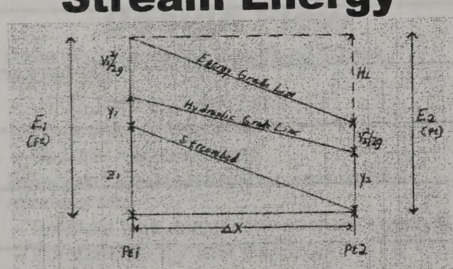
  $Q_{in} - Q_{out} = \Delta Storage$
- **Applications to SHM**



Law of Conservation of Energy

- **"In hydraulic system, energy not lost, but can be converted to other forms"**
- **Three forms of stream energy**
  - Kinetic, energy of motion ($V^2/2g$, ft)
  - Pressure, energy of depth (y, ft)
  - Elevational, potential energy (Z, ft)

Stream Energy



$$V_1^2/2g+y_1+Z_1=V_2^2/2g+y_2+Z_2+H_L$$

Bernoulli's Equation

Specific Energy (E_S) Diagram

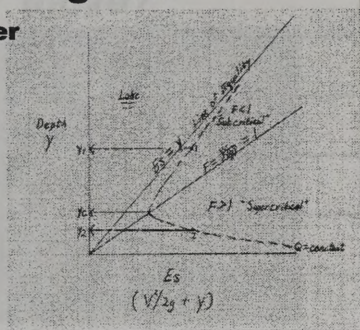
Froude Number
$F=V/(gy)^{1/2}$

Ratio of kinetic to depth energy

F<1, sub-critical (deep and slow)

F>1, super-critical (shallow and fast)

F=1, critical flow (transitional)



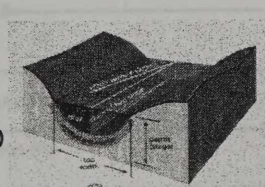
Energy Law Applications

- **Explains flow condition across structures**
- **Sub-critical provides most habitat**
- **Super-critical**
  - **Scour**
  - **Sediment transport**
  - **Long-term habitat creation and maintenance**
- **Hydraulic controls**
  - **Stage-discharge relations**
  - **Pool-riffle transition**
- **Basis for Manning Equation**

Manning's Equation
(and the "ideal" channel)

$V=(1.49/n)R^{2/3}S^{1/2}$
Or
$Q=(1.49/n)AR^{2/3}S^{1/2}$

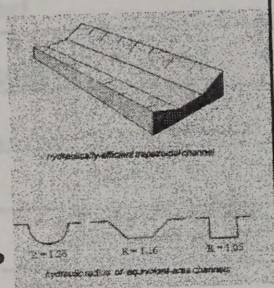
Where:
V= velocity (ft/sec)
A= cross-sectional area (ft²)
R= hydraulic radius (ft)
S= water surface slope (ft/ft)
Q= streamflow (ft³/sec)
n= Manning's roughness coefficient



FISRWG 1998

Manning's Equation
(and the "ideal" channel)

- Assumes "uniform" flow with S, D, W, and V constant
- "Ideal" channel for conveyance maximizes R
- R maximized with "half-circle" cross section
- Q maximized with minimum "n"
- Resulted in smooth, straight, trapezoidal channels
- Channelization has led to need for SHM



Newbury 1994

Manning's "n"
(Q~1/n)

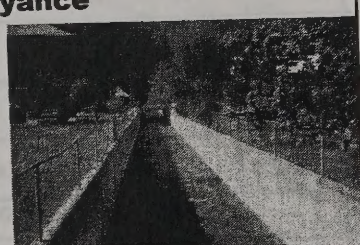
FISRWG 1998

Table 7.2: Manning roughness coefficients for various boundaries.
Source: Ven te Chow 1964.

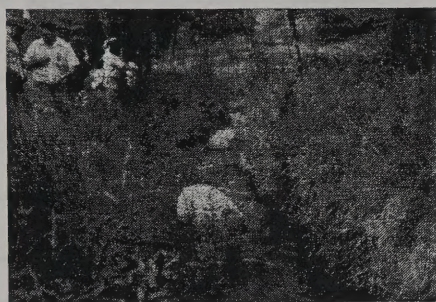
Boundary	Manning Roughness, n Coefficient
Smooth concrete	0.012
Ordinary concrete lining	0.013
Vitrified clay	0.015
Shot concrete, untroweled, and earth channels in best condition	0.017
Straight unlined earth canals in good condition	0.020
Rivers and earth canals in fair condition—some growth	0.025
Winding natural streams and canals in poor condition—considerable moss growth	0.035
Mountain streams with rocky beds and rivers with variable sections and some vegetation along banks	0.040-0.050
Alluvial channels, sand bed, no vegetation	
1. Lower regime	
Ripples	0.017-0.028
Dunes	0.018-0.035
2. Washed-out dunes or transition	0.014-0.024
3. Upper regime	
Plane bed	0.011-0.015
Standing waves	0.012-0.016
Antidunes	0.012-0.020

Channelization

- Uniform flow
- High conveyance
- Low "n"
- Straight
- Smooth
- SHM

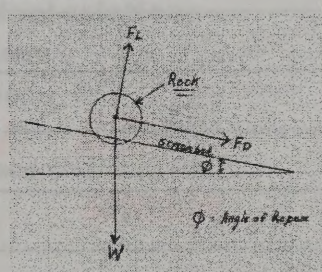


Why do stream sediments move?



Why Do Stream Sediments Move?

Applied force greater than resisting force



Concept of shear stress

- **Applied force on channel boundary function of flow, slope and shape**
  - $T_0 = \gamma_W RS$
    - Where:
      - » T_0 = shear stress (lbs/ft^2)
      - » γ_W = 62.4 lbs/ft^3 ← specific wt of H_2O
      - » R=hydraulic radius (ft)
      - » S = slope (ft/ft)

Concept of shear stress

- **Resisting force function of particle size and weight**

  $T_c=k(\gamma_s-\gamma_w)d$ $= lbs/ft^2$

  - Where:
    - T_c=critical shear stress
    - k = Shield's parameter; 0.03 for cobble bed streams
    - γ_s= Specific weight of sediment (165lbs/ft³)
    - γ_w = Specific weight of water (62.4 lbs/ft³)
    - d = particle diameter (ft)

k will vary a lot depending on size of the cobble & distribution of the large rocks to the K.

Concept of shear stress

- **If $T_0<T_c$, particle stays in place**
- **If $T_0>T_c$, particle moves**
- **When $T_0=T_c$, threshold of motion**

Concept of shear stress

- **Some empirical relations**
  - Shield's diagram

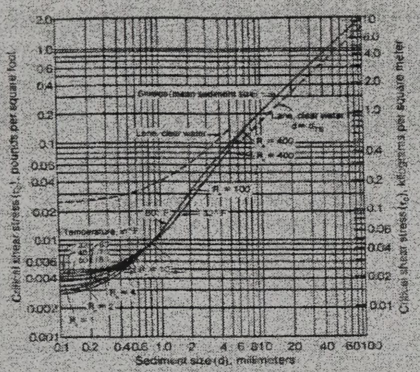


Figure 5.3 Critical shear stress for quartz sediment in water as function of grain size.

3.3 ft/m

$3.3 \times \frac{10}{2} = \frac{30}{15}$

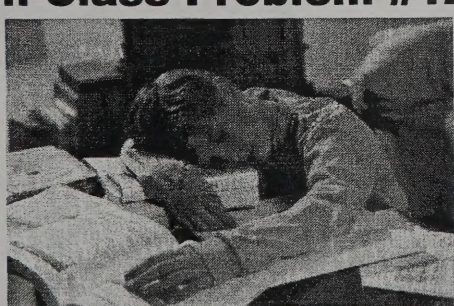
2.5

~~2.4~~

Concept of shear stress

- **Some empirical relations**
  - –Shield's diagram
  - –Lane's Relation
    - $T_c = 0.164 d_{75}$ ← same as diameter of the particle — regression   (d_{75} in mm; cm written above) metric drives engineers nuts
  - –Highway Research Board Relation
    - $T_c = 4 d_{50}$ (d_{50} in ft)

In-Class Problem #12



Will The Boulder Move?

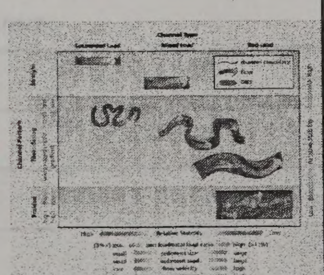
- Given D_w=3.0 ft, S=0.04, will a 2.0 ft diameter boulder move?
- Solve using Shield's, Lane's and HRB's equations
- Different answers? What do you do?

Channel Morphology

Template for SHM

Using Channel Classification as a Guide

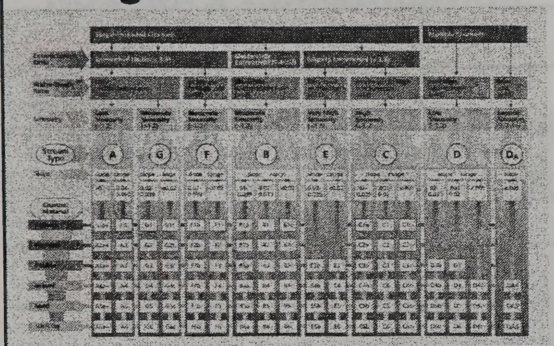
- **Schumm's system**
  - Stability inference
  - Little SHM design insight



From FISRWG 1998

system for calling a stream an A type + so on

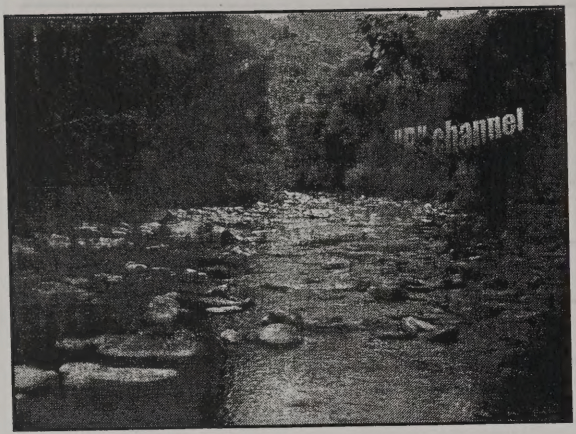
Rosgen's Classification

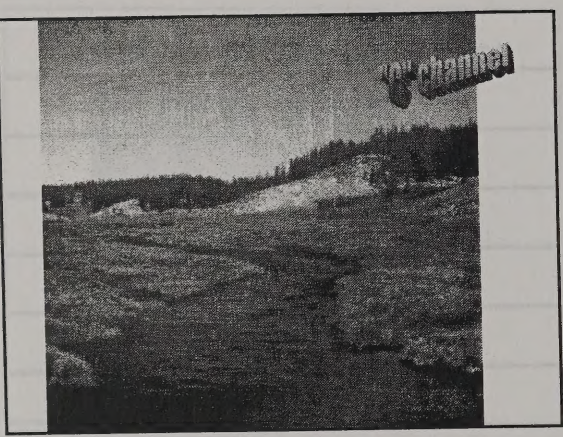


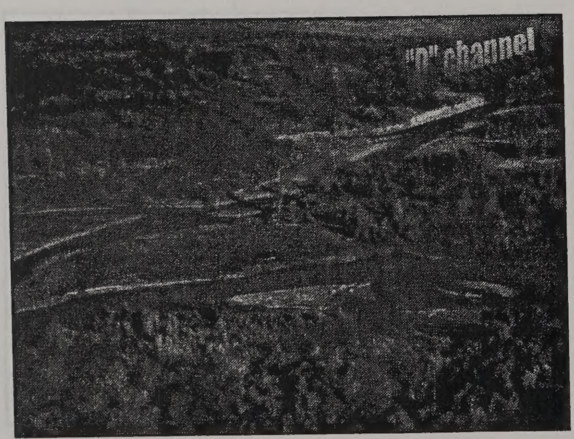
FISRWG 1998

Rosgen's Classification

- **Level I**
  - Broad level stream types
  - Slope, planform and sinuosity
  - Few SHM implications by itself
  - Examples

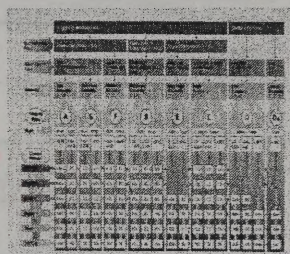

channel


"D" channel


"D" channel

Rosgen's Classification

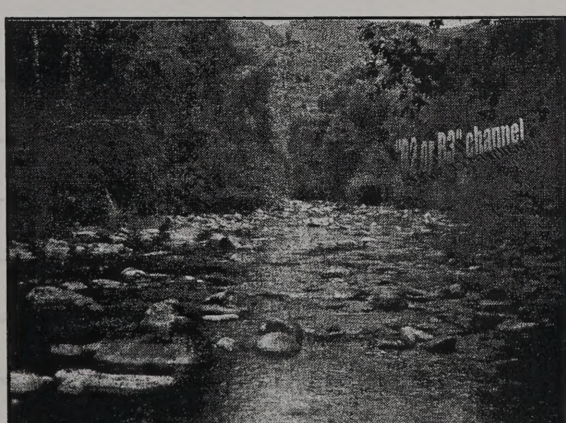
- **Level II, morphologic description**
  - Stratifies major types into sub-types
  - Substrate, W/D, and entrenchment
  - Guidance for SHM by sub-type

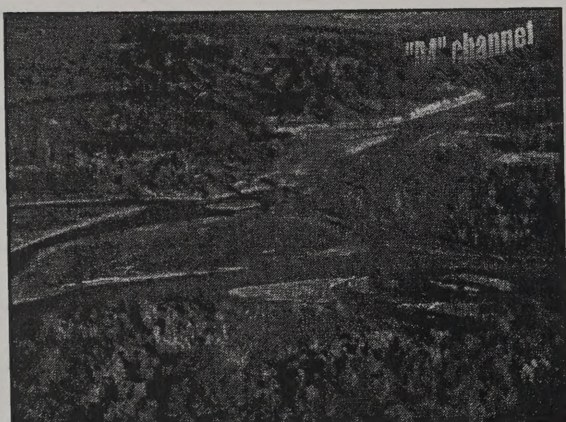


FISRWG 1998

Critism of Dave Rosgen's Classification system is that it has not been tested

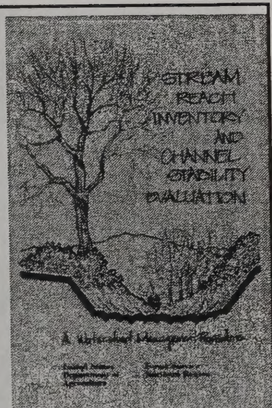
Class system is beginning to be used a lot by managers.



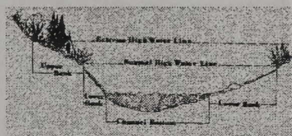


SRI/CSE

- Pfankuch 1975
  - (Handout)
- Ocular, rapid assessment
- Numerical rating
- Forest streams
- Adapt to conditions



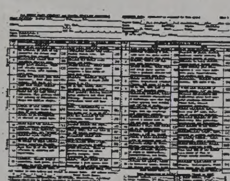
SRI/CSE



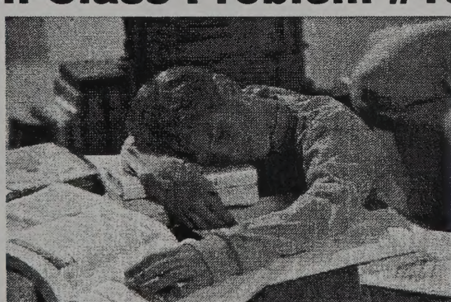
- **Upper banks**
  - Bank slope
  - Mass wasting potential
  - Debris jam potential
  - Vegetative bank protection
- **Lower banks**
  - Channel capacity
  - Bank rock content
  - Obstructions/deflectors/traps
  - Cutting
  - Deposition
- **Channel bottom**
  - Rock angularity
  - Brightness
  - Particle packing
  - Stable materials
  - Scour and deposition
  - Aquatic vegetation

SRI/CSE Scoresheet

- **"Good" = 38-76**
- **"Fair" = 77-114**
- **"Poor" = 115+**
- **Condition class may vary by channel type (Rosgen 1996)**

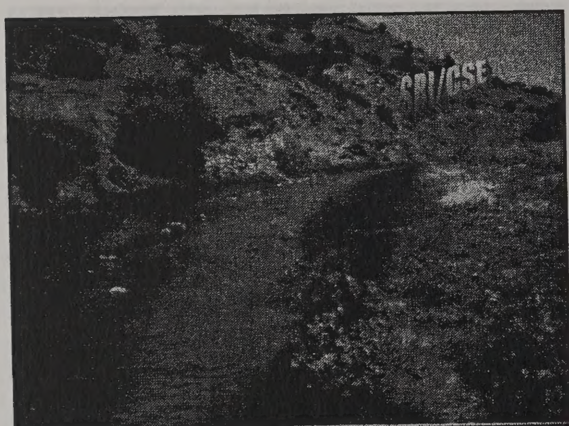


In-Class Problem #13

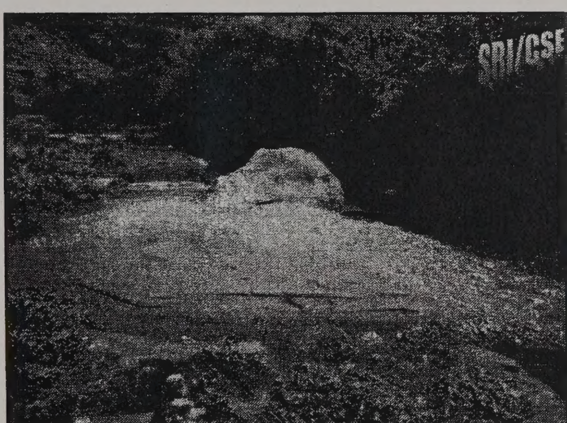


Applying SRI/CSE

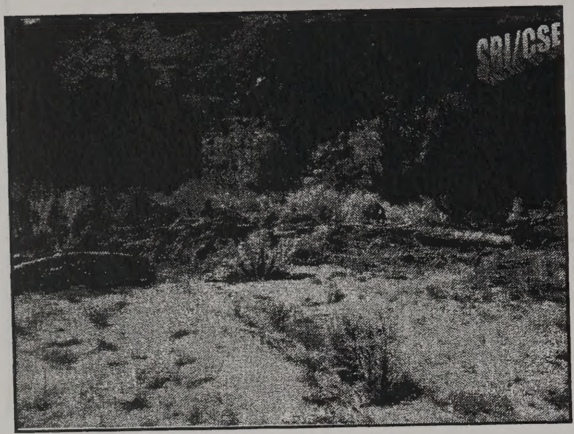
- **Review slides of Sante Fe River below Sante Fe**
- **Using field forms, rate the 15 parameters**
- **Tally scores and determine condition class**
- **Discussion**

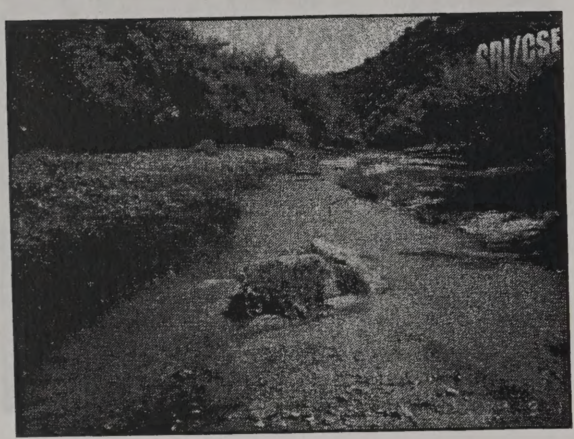



SRI/CSE


SRI/CSE


SRI/CSE





Assessing Condition

Comparing test and reference streams

Assessing Condition Quick Review

- Macrohabitat characteristics
- Mesohabitat characteristics
- Microhabitat characteristics
- HSI
- Channel classification
- SRI/CRE

Assessing Condition

- Identify habitat deficiencies
- Quantify habitat deficiencies
- Develop boundaries and criteria for SHM
- Don't try to make stream something it can not be!
- *Good old fashion observation*

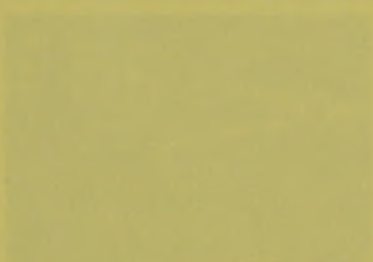
Assessing Condition

- **Good old-fashioned observation**
  - Where do fish hang out?
  - What structure forms feeding lanes?
  - What size of substrate is stable?
  - Are boulders naturally clustered?
  - Are scour pools present below boulders? How deep?
  - Are pools and riffles well-defined and stable?
  - How deeply is large wood anchored?
  - What size wood comprise stable debris jams?
  - How deeply undercut are streambanks?
  - What shape are most bed particles? Round? Angular?
  - How high in relation to bankfull channel are point bars?
  - Are point bars vegetated?
  - Are mid-channel bars present? Common?
- **Discussion**

Day 4 Afternoon

[illegible]

Tools of the Trade



[illegible]

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Day 4 Afternoon

- **Role of SHM in aquatic habitat restoration: Is there one?**
- **Planning and implementing SHM projects**
- **Workshop: "Art and Science of SHM"**
  - Review of governing physical principles and properties
  - Tools of the trade; Design criteria and uses for common structural treatments

Tools of the Trade

Design criteria and uses for common SHM treatments

Overpour Structures

Weirs, check dams, plunges, berms and sills

Overpour Structures

- **Purposes**
  - Create downstream scour pool
  - Promote upstream water and sediment storage
  - Improve passage conditions at culverts
  - Encourage downstream gravel bar formation
  - Facilitate aeration
  - Reduce excess water velocities
  - Collect and hold gravels upstream
  - Stabilize down-cut channels
  - Control flow into secondary channels

Overpour Structures

- **Design**
  - Commonly built of logs, ties, rock or wire
  - Configuration straight, upstream U or V, downstream U or V, W pattern transverse
  - Wood structures often have low flow notch
  - Typically less than 75% bankfull height (don't create a passage barrier!)

Overpour Structures

- **Design**
  - Typical log overpour

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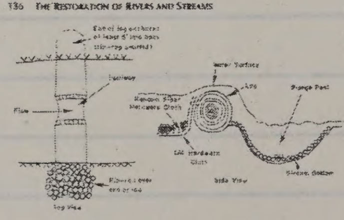
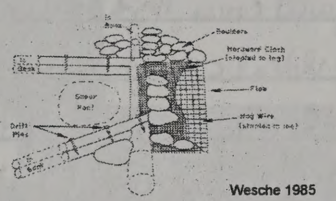


Figure 5.6 Single log dam.

Wesche 1985

Overpour Structures

- **Design**
  - K-dam



Wesche 1985

Overpour Structures

- **Design**
  - Rock berm

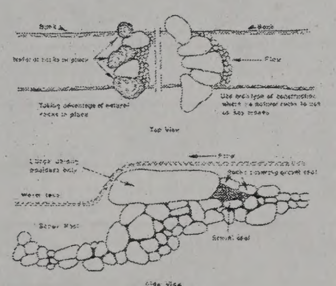
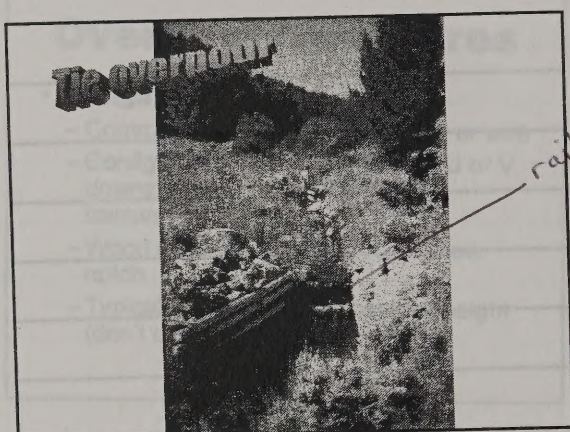


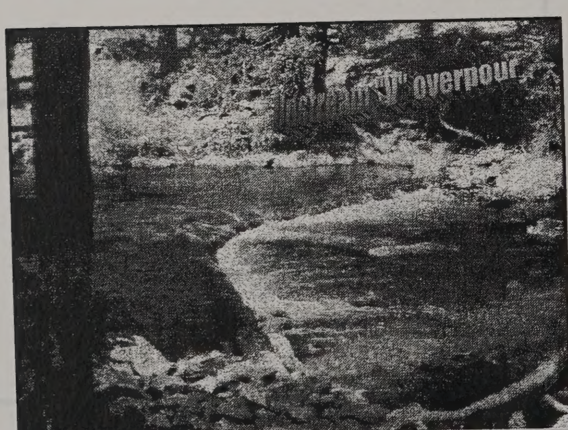
Figure 3.4 Boulder dam.

Wesche 1985

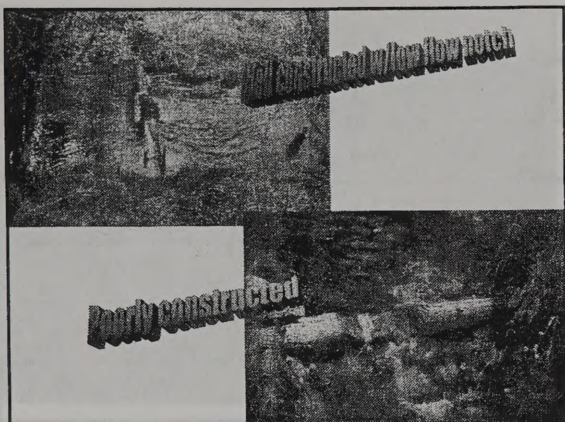
Lateral pressure behind the log will cause the stream to move. Ideal conditions were create behind the log for fish. If this was the objective you must realize the need for maintenance

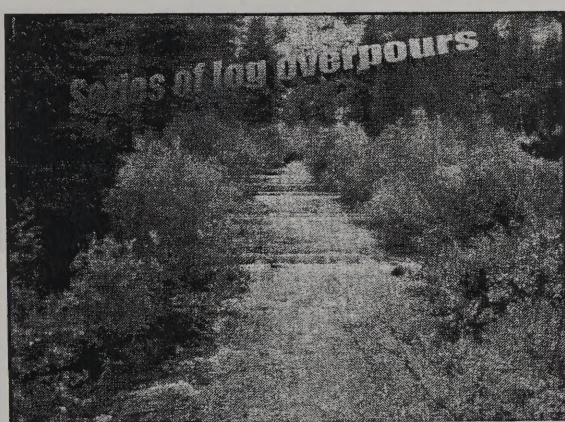


railroad tie



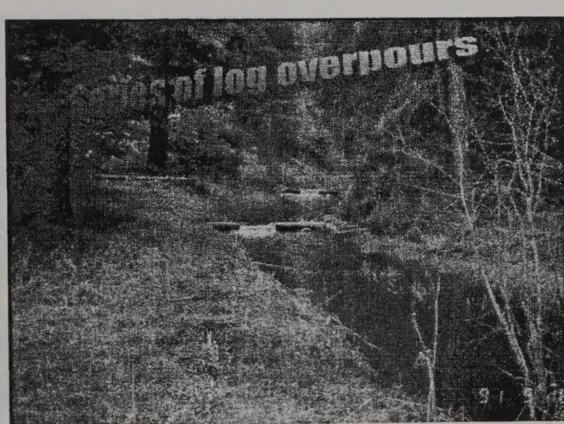
V overpour encourages scour in the center of the stream.

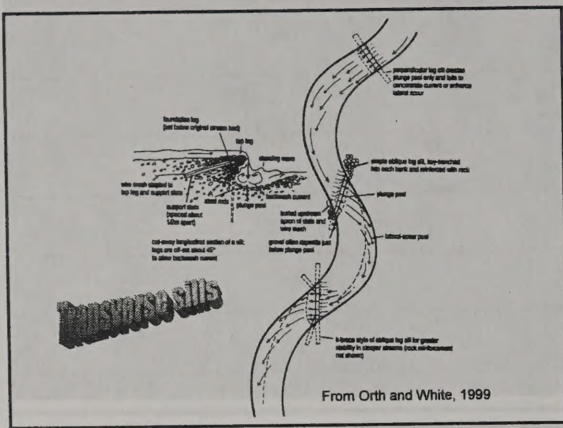




Too many within the reach. Need, rule of thumb, 4-5 times the stream width upstream length to build an adequate riffle set + pool

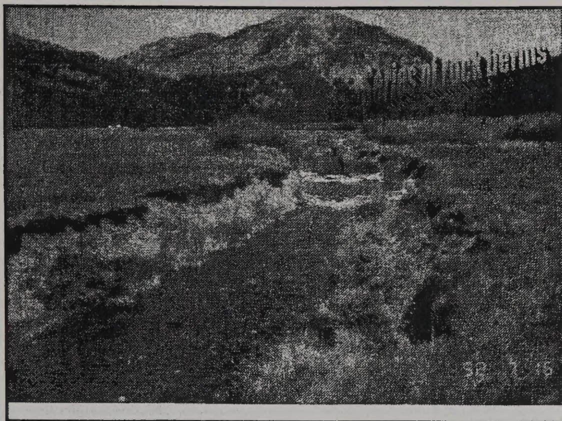
per Leopold

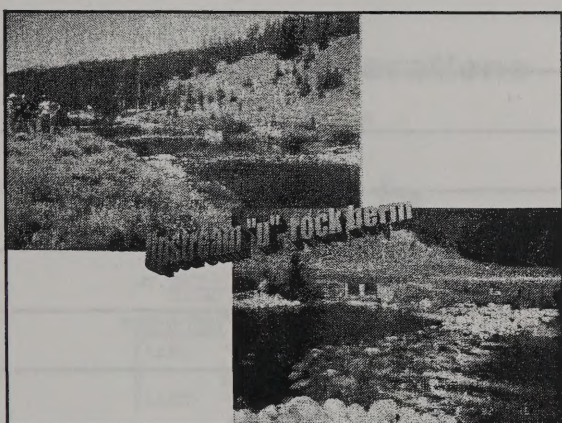


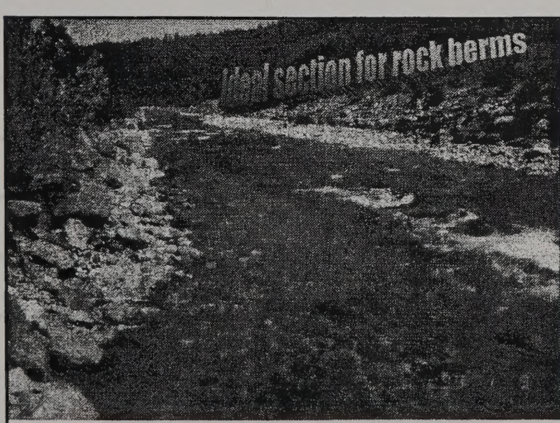

Transverse sills
From Orth and White, 1999

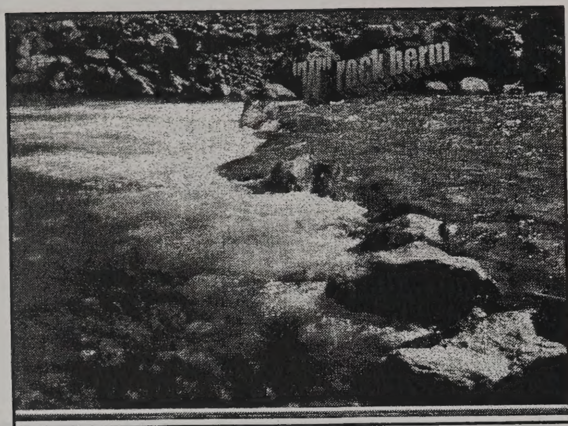

Rock berm


ock berm to stabilize meander

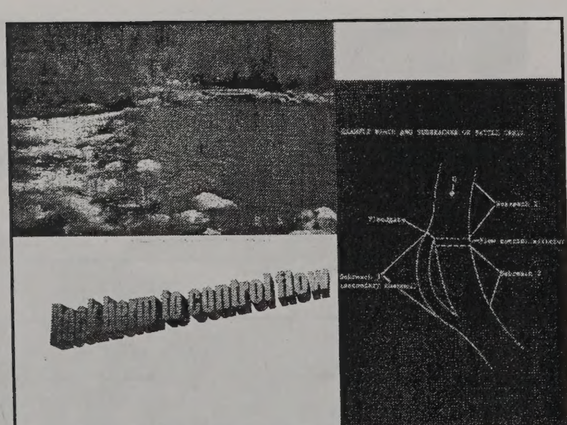

Series of rock berms


Upstream "u" rock berm


Ideal section for rock berms


rock berm


Blown out rock berm

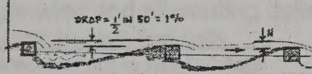

Rock berm to control flow

Overpour Siting

- **Low dams (<1/3 bankfull height) excellent/good in channel types B2,3,4,5,6 (Rosgen 1996)**
- **Medium dams (1/3 – ¾ bankfull height) excellent/good in B2,3, and 4 (Rosgen 1996)**
- **Pool-deficient straight or sinuous reaches on small stream (W=1-9m)**
- **Generally space no closer than 5-7 channel widths apart (no drown out!)**
- **Stable bed and banks preferred, with bank anchoring a necessity**

Hydraulic Considerations

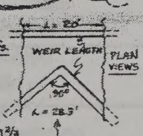
- HABITAT IMPROVEMENT STRUCTURES INSTALLED IN NATURAL CHANNEL:



- WEIR FLOW EQUATION

$Q = C\,L\,(H)^{3/2}$; $Q = 222$ cfs.

IF: COEFF. $C = 2.5$ ASSUMING SMALL SUB-SURFACE FLOW



- SOLVE FOR HEAD H ON EACH WEIR:

$L = 20'$, $H = \left[\frac{Q}{(2.5)(20)}\right]^{2/3}$

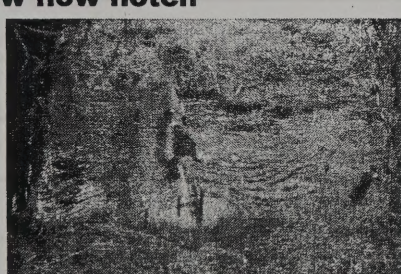
$H = 2.7$ ft.

$L = 28.3'$, $H = \left[(222/(2.5)(28.3)\right]^{2/3}$

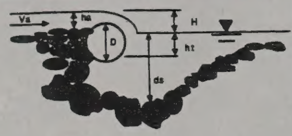
$H = 2.1$ ft.

Hydraulic Considerations

- **Low flow notch**



Hydraulic Considerations



PROFILE

Scour below Log Weir

$d_s = f(\Delta H, G, \gamma_t, \gamma_a, Q, B, g)$

$d_s = 3.27 \frac{\delta^{0.6} \Delta H^{0.05} h^{0.15}}{g^{0.30} d_m^{0.10}} = \text{Scour\_Depth}$

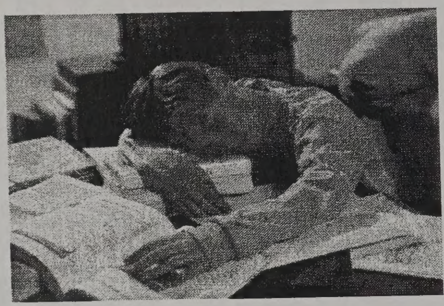
$\delta = {}^{Q_w}/_{w}$

$\Delta H = \gamma_t$ = tailwater depth from original bed

$d_m = d_{50}$ of substrate

g=gravitational acceleration

In Class Problem #14



Evaluating Overpour Hydraulics

- **A log overpour structure is being planned for a small stream**
- **Based upon the proposed design, the design flows and the channel morphology data provided, apply the weir flow equation to determine:**
  - The proper size of the notch
  - The stage of the upstream pool at high design flow
- **Should out-of-channel flooding be predicted at high flow, what design modifications could be made to prevent it?**

Deflectors and Constrictors

Deflectors and Constrictors

- **Purposes**
  - Single wing and alternating deflectors
    - Create sinuous flow path
    - Direct current to key habitats
    - Deepen and narrow channel
    - Protect banks from erosion
    - Enhance pool-riffle ratio
    - Consolidate low flows
    - Encourage riparian vegetation
    - Clean spawning and rearing substrates

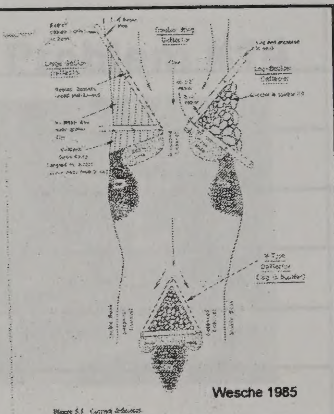
Deflectors and Constrictors

- **Purposes**
  - Opposing or double-deflectors
    - Create mid-channel scour pool
    - Encourage downstream bar formation
    - Enhance habitat diversity

Deflectors and Constrictors

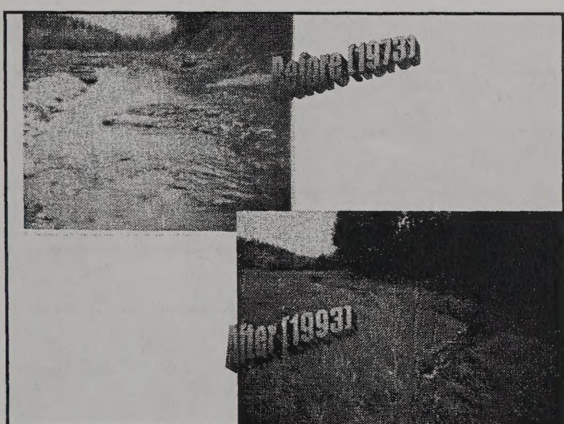
- **Design**
  - Commonly wood, rock, or wood and rock
  - Typically triangular in shape with upstream face angling downstream, and downstream face perpendicular to flow or angling upstream
  - "Barbs" on outside of eroding meanders directed slightly upstream
  - Single wings extend up to 50% of channel width
  - Opposing wings reduce channel width 40-80%
  - Typically less than 75% bankfull height
  - Must be well anchored into bank

Deflector Design

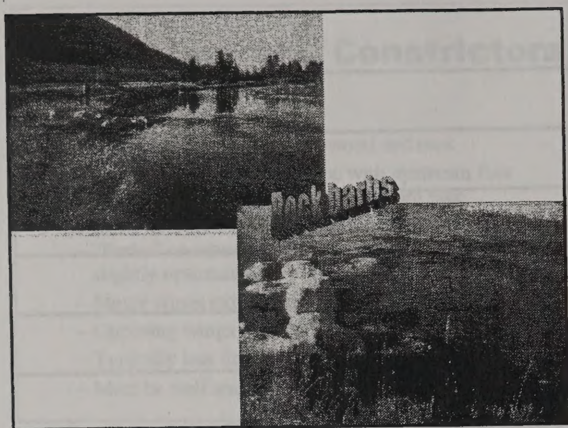


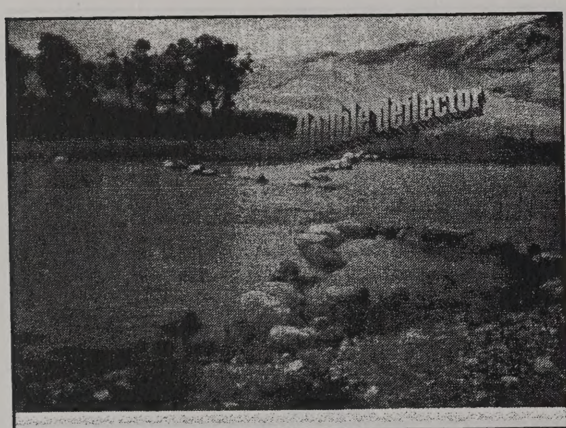
Wesche 1985


wing deflectors


Before (1973)
(1993)


failed deflector


Rock barbs


Double deflector


Rock funnel

Deflector Siting

- Generally excellent/good in channel types B2,3,4,5 and 6, C2 and 3, and F3 (Rosgen 1996)
- Typical placement in wide, shallow, straight streams
- Excellent for channelized reaches
- Alternating wings typically spaced 5-7 channel widths apart
- Bank opposite deflector must be stable or be stabilized
- Avoid using opposing deflectors in channels carrying high debris loads
- Use not limited to only small streams

Hydraulic Considerations

- **Continuity equation can be used to estimate W, D, A, V changes**
- **WinXSPRO can model hydraulics and sediment transport**
- **Susceptible to scour at apex of triangle**
- **"Barbs" susceptible to scour at upstream notch**

Substrate Modification

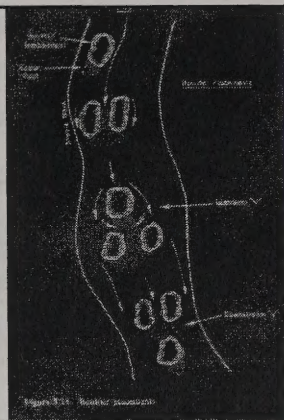
For rearing and spawning

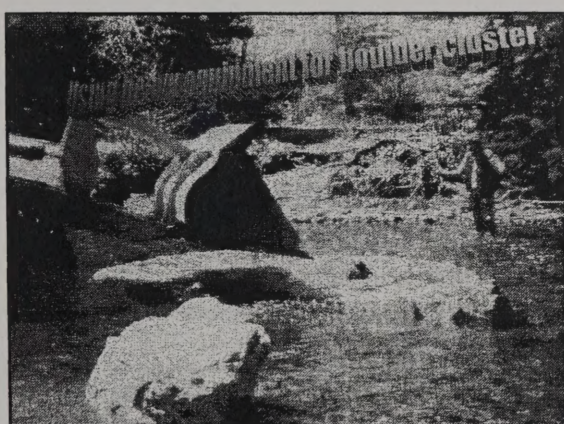
Boulder Placements

- **Purposes**
  - –Provide rearing habitat
  - –Provide cover
  - –Create pocket water
  - –Gravel trapping

Boulder Placement Design

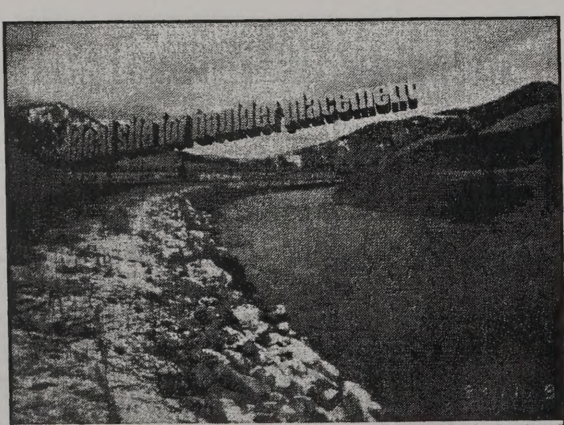
- Typically 0.6-1.5 m diameter rocks
- Angular rock preferred to round
- Harder the rock the better
- Embed in substrate
- Clusters of 2 or more give greater diversity
- Place longest axis parallel to flow






big for channel


Before
After

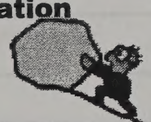


Boulder Placement Siting

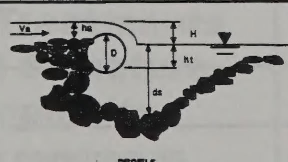
- Excellent/good for channel types B3, B4, and C3 (Rosgen 1996)
- Place single rocks or clusters in thalweg of low flow channel
- Avoid depositional areas
- Avoid unstable substrates
- Rocks placed no closer than 2 boulder widths from bank
- Excellent for channelized or "tie–driven" streams

Hydraulic Considerations

- **Evaluate threshold of motion with shear stress relations**
- **Observation of stable boulders in reference reach helpful**
- **Could evaluate scour potential using weir scour equation**



Hydraulic Considerations



Scour below Log Weir

$$d_s = f(\Delta H, G, \gamma_t, \gamma_a, Q, B, g)$$

$$d_s = 3.27\frac{\delta^{0.6}\Delta H^{0.05}h^{0.15}}{g^{0.30}d_m^{0.10}} = Scour\_Depth$$

$$\delta = {}^{Q_w}/_{w}$$

$\Delta H = \gamma_t$ = tailwater depth from original bed

$d_m = d_{50}$ of substrate

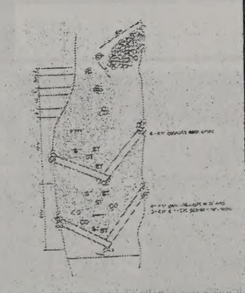
g=gravitational acceleration

Spawning Substrate Development

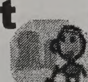
- **Overpour structures**
- **Deflectors**
- **Boulder clusters**
- **Re-introduction of flow into abandoned channels**
- **Log sill gravel traps**
- **Gravel placement**

Log Sill Gravel Traps

- **Single log structure similar to overpour, but lower profile**
- **Typically straight or downstream "V" shape**
- **Often placed in pairs**
- **Excellent/good in channel types B1,2,3 and C1,2 and 3**

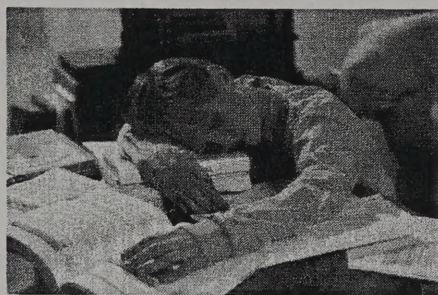


Gravel Placement



- Size specific to target species
- Piles can be placed every 5-7 channel widths and distributed by flow (Stuart 1953)
- Small placements of $>2ft^2$ can be effective in channel types B3, C2, C3 (Rosgen 1996)
- Artificial spawning channels could be effective in tailwaters
- Evaluate threshold of motion with shear stress relations or bedload transport models

In Class Problem #15



Using WinXSPRO to Evaluate Spawning Gravel Placememt

- Gravel placement is being considered for cutthroat trout spawning
- Based upon hydraulics, design flow and gravel suitability, use WinXSPRO to evaluate stability as described in problem
- If unstable, analyze further to determine a suitable substrate size that still meets species needs
- Discussion

Additional Treatments for Habitat Structure and Complexity

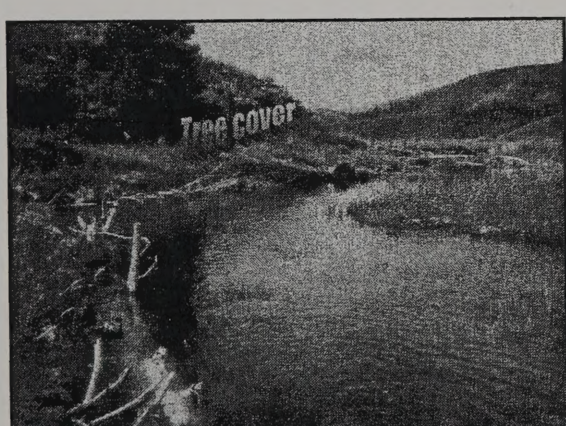
- **Tree retards or revetments**
- **Tree covers**
- **Rootwads**
- **Half-logs**
- **Others**

Tree Retards or Revetments

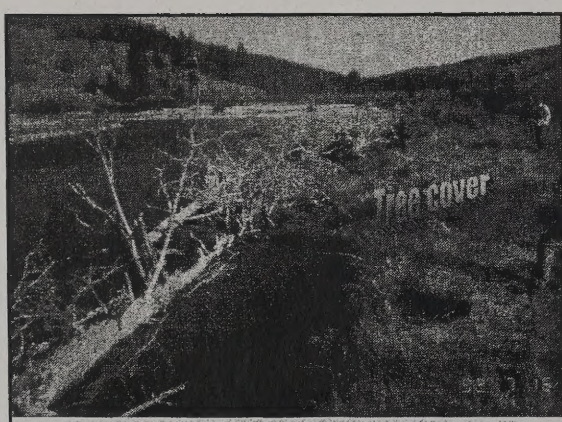
- Provides habitat and stabilization: good "silt catchers"
- Often used along out ~~in~~side of eroding meander bends
- Conifers best, junipers preferred
- Use largest trees that can be handled
- Overlap at least 50% with crowns angled downstream
- Anchor with buried deadman and cable
- Can be used with willow plantings

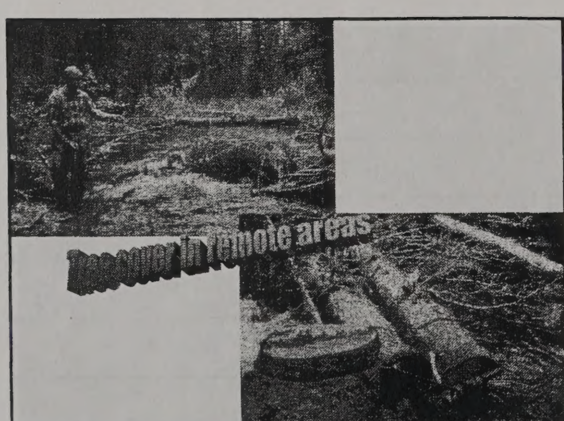
Tree Covers

- Provide cover and accumulate debris
- Often attached to overpour structures to enhance pool quality



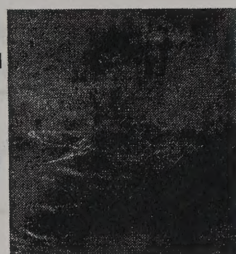

Tree cover with deflector


Tree cover


Tree cover in remote areas

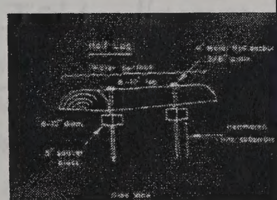
Rootwads

- Provides cover and accumulates debris
- Tree bole anchored well into bank with roots extending into low flow channel to scour hole
- Can be set on footer log and backfilled with boulders
- Can be used in series much like tree retard on eroding meanders



Half-logs

- Provide in-channel overhead cover
- Site near major flow concentration, not in depositional areas
- Generally excellent/good in B and C channel types (Rosgen 1996)



Additional Sources

- Hunt, R.L. 1993. Trout stream therapy. University of Wisconsin Press, Madison. 74p.
- Hunter, C.J. 1991. Better trout habitat: A guide to stream restoration and management . Island Press, Washington, D.C. 320p.
- Rosgen, D. 1996. Applied river morphology. Wildland Hydrology, Pagosa Springs, Co.
- Wesche, T.A. 1985. Modifications and structures to enhance fish habitat. Chapter 5, in , J.A. Gore (ed) The restoration of rivers and streams, theories and experience. Butterworth Publishers, Boston. 280p.

Successes + failures +
generally NOT documented

Consideration of *Uncertainty* in SHM

- **Why be concerned?**
  - –Compare risk of different treatments at a site
  - –Compare different sets of treatments for a reach
  - –Compare risks between reaches

From Johnson and Brown, 2001 (Handout)

might have general applicability to other RM actions

Sources of *Uncertainty*

- Model uncertainty
- Parameter uncertainty
- Randomness
- Human error

Evaluating Failure

- Failure mode
- Effects of other treatments
- Effects on the whole system
- Detection methods
- Compensating provision

Assigning Risk Priority Numbers

- Criteria for consequences
- Occurrence likelihood
- Detection of failure
- Developing risk priority numbers

Criteria for Consequences

- **Loss of life**
- **Economic impacts**
- **Aquatic habitat impact**
- **Public scrutiny**
- **Ratings**
  - Low = 1
  - Marginal = 4
  - High = 7
  - Critical = 10

Occurrence Likelihood

Impossible =2
Remotely possible = 4
Possible = 6
Probable = 8
Reasonably probable = 10

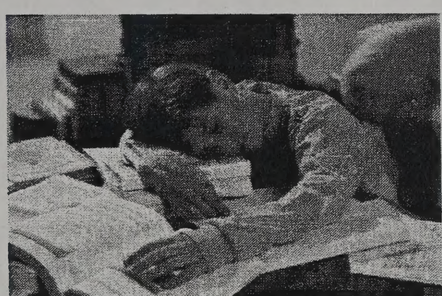
Detection of Failure

- **Very simple, visual =1**
- **Simple, analysis of photos, bank pins, etc... = 4**
- **Somewhat complex (e.g. cross section surveys) = 7**
- **Quite complex (e.g. pressure transducers) = 10**

Developing Risk Priority Numbers

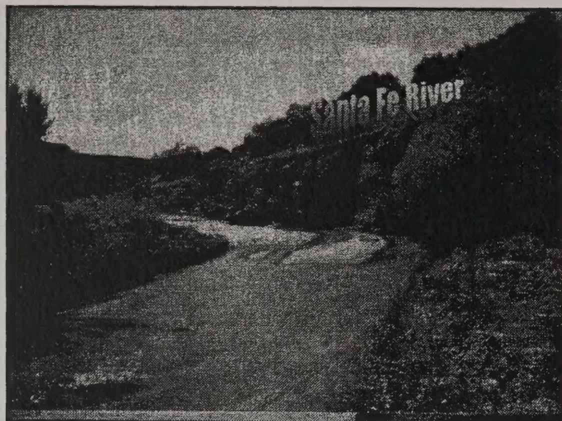
- Multiply the three ratings for each treatment
- Sum treatment scores to obtain project total
- Discussion

In Class Problem #16

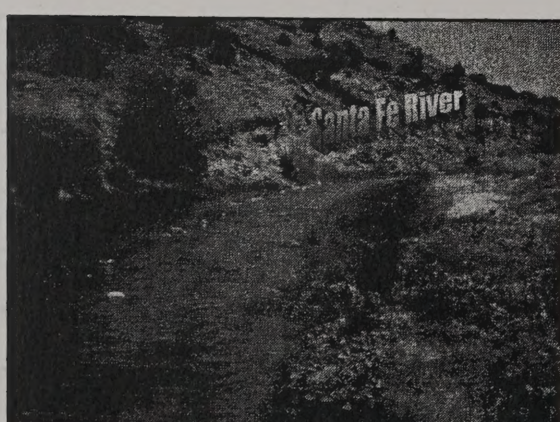


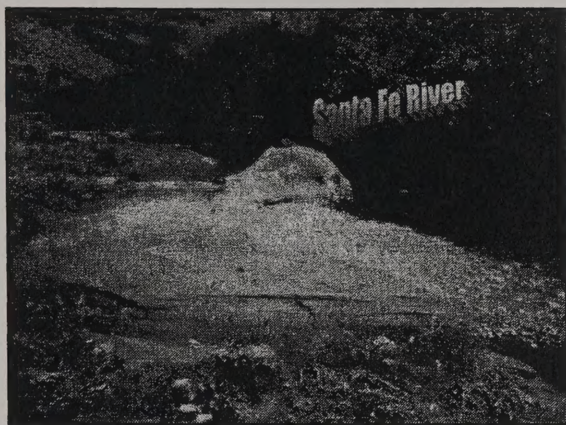
Santa Fe River SHM Problem

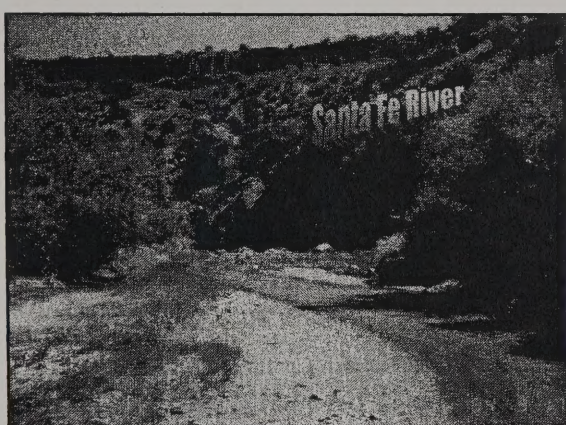
- Review slides of Santa Fe River below Santa Fe, NM
- Work in pairs
  - Develop list of possible SHM treatments
  - Using cutthroat HSI model assess which variables will be affected by recommended treatments, and to what degree
  - Develop list of additional measures
- Class discussion

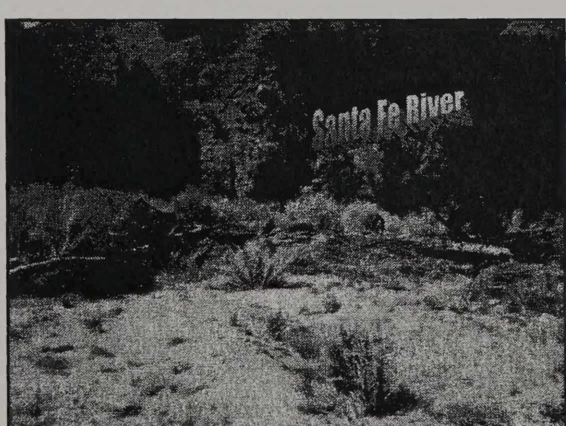

Santa Fe River


Santa Fe River


Santa Fe River


Santa Fe River


Santa Fe River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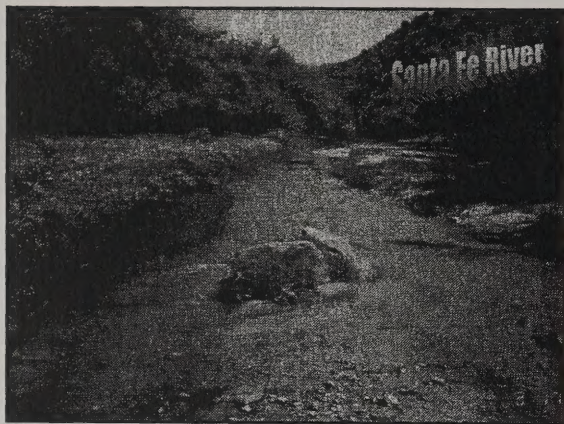
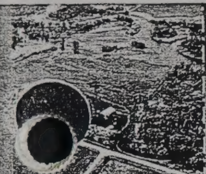
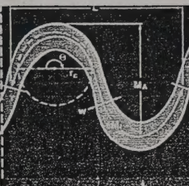


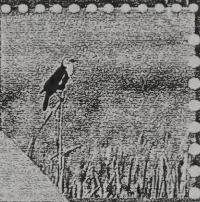
Santa Fe River

Wrap-up!

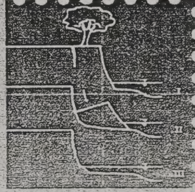
Handouts

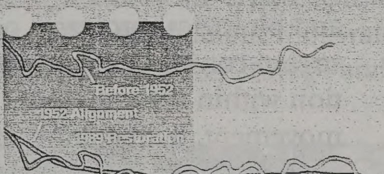



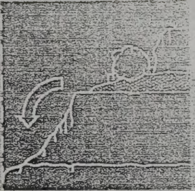

Stream Corridor Restoration




Principles, Processes, and Practices




October 1998

Introduction

Stream Corridor Restoration: Principles, Processes, and Practices

There is a phenomenal resiliency in the mechanisms of the earth. A river or lake is almost never dead. If you give it the slightest chance...then nature usually comes back.

— Rene Dubos 1981

Why Is Stream Corridor Restoration Important?

The United States has more than 3.5 million miles of rivers and streams that, along with closely associated floodplain and upland areas, comprise corridors of great economic, social, cultural, and environmental value. These corridors are complex ecosystems that include the land, plants, animals, and network of streams within them. They perform a number of ecological functions such as modulating streamflow, storing water, removing harmful materials from water, and providing habitat for aquatic and terrestrial plants and animals. Stream corridors also have vegetation and soil characteristics distinctly different from surrounding uplands and support higher levels of species diversity, species densities, and rates of biological productivity than most other landscape elements.

Streams and stream corridors evolve in concert with and in response to surrounding ecosystems. Changes within a surrounding ecosystem (e.g., watershed) will impact the physical, chemical, and biological processes occurring within a stream corridor. Stream systems normally function within natural ranges of flow, sediment movement, temperature, and other variables, in what is termed "dynamic equilibrium." When changes in these variables go beyond their natural ranges, dynamic equilibrium may be lost, often resulting in adjustments in the ecosystem that might conflict with societal needs. In some circumstances, a new dynamic equilibrium may

Fig. I.1: Stream corridor in the Midwest. *Stream corridors have great economic, social, cultural, and environmental values.*

eventually develop, but the time frames in which this happens can be lengthy, and the changes necessary to achieve this new balance significant.

Over the years, human activities have contributed to changes in the dynamic equilibrium of stream systems across the nation. These activities center on manipulating stream corridor systems for a wide variety of purposes, including domestic and industrial water supplies, irrigation, transportation, hydropower, waste disposal, mining, flood control, timber management, recreation, aesthetics, and more recently, fish and wildlife habitat. Increases in human population and industrial, commercial, and residential development place heavy demands on this country's stream corridors.

The cumulative effects of these activities result in significant changes, not only to stream corridors, but also to the ecosystems of which they are a part. These changes include degradation of water quality, decreased water storage and conveyance capacity, loss of habitat for fish and wildlife, and decreased recreational and aesthetic values (National Research Council 1992). According to the 1994 National Water Quality Inventory of 617,806 miles of rivers and streams, only 56 percent fully supported multiple uses, including drinking water supply, fish and wildlife habitat, recreation, and agriculture, as well as flood prevention and erosion control. Sedimentation and excess nutrients were the most significant causes of degradation (USEPA 1997) in the remaining 44 percent.

Human activity has profoundly affected rivers and streams in all parts of the world, to such an extent that it is now extremely difficult to find any stream which has not been in some way altered, and probably quite impossible to find any such river.

— H.B.N. Hynes 1970

Fig. I.2: Concrete-lined channel. *Stream systems across the nation have been altered for a wide variety of purposes.*

Given these statistics, the potential for restoring the conditions in our nation's rivers and streams and protecting them from further damage is almost boundless.

What Is Meant by Restoration?

Restoration is a complex endeavor that begins by recognizing natural or human-induced disturbances that are damaging the structure and functions of the ecosystem or preventing its recovery to a sustainable condition (Pacific Rivers Council 1996). It requires an understanding of the structure and functions of stream corridor ecosystems and

Restoration, Rehabilitation, and Reclamation

- **Restoration** *is reestablishment of the structure and function of ecosystems (National Research Council, 1992). Ecological restoration is the process of returning an ecosystem as closely as possible to predisturbance conditions and functions. Implicit in this definition is that ecosystems are naturally dynamic. It is therefore not possible to recreate a system exactly. The restoration process reestablishes the general structure, function, and dynamic but self-sustaining behavior of the ecosystem.*
- **Rehabilitation** *is making the land useful again after a disturbance. It involves the recovery of ecosystem functions and processes in a degraded habitat (Dunster and Dunster 1996). Rehabilitation does not necessarily reestablish the predisturbance condition, but does involve establishing geological and hydrologically stable landscapes that support the natural ecosystem mosaic.*
- **Reclamation** *is a series of activities intended to change the biophysical capacity of an ecosystem. The resulting ecosystem is different from the ecosystem existing prior to recovery (Dunster and Dunster 1996). The term has implied the process of adapting wild or natural resources to serve a utilitarian human purpose such as the conversion of riparian or wetland ecosystems to agricultural, industrial, or urban uses.*

Restoration differs from rehabilitation and reclamation in that restoration is a holistic process not achieved through the isolated manipulation of individual elements. While restoration aims to return an ecosystem to a former natural condition, rehabilitation and reclamation imply putting a landscape to a new or altered use to serve a particular human purpose (National Research Council 1992).

the physical, chemical, and biological processes that shape them (Dunster and Dunster 1996).

Restoration, as defined in this document, includes a broad range of actions and measures designed to enable stream corridors to recover dynamic equilibrium and function at a self-sustaining level. The first and most critical step in implementing restoration is to, where possible, halt disturbance activities causing degradation or preventing recovery of the ecosystem (Kauffman et al. 1993). Restoration actions may range from passive approaches that involve removal or attenuation of chronic disturbance activities to active restoration that involves intervention and installation of measures to repair damages to the structure of stream corridors.

Restoration practitioners involved with stream corridors take one of three basic approaches to restoration:

- *Nonintervention and undisturbed recovery:* where the stream corridor is recovering rapidly, and active restoration is unnecessary and even detrimental.
- *Partial intervention for assisted recovery:* where a stream corridor is attempting to recover, but is doing so slowly or uncertainly. In such a case, action may facilitate natural processes already occurring.
- *Substantial intervention for managed recovery:* where recovery of desired functions is beyond the repair capacity of the ecosystem and active restoration measures are needed.

The specific goals of any particular restoration should be defined within the context of the current conditions and disturbances in the watershed,

Streams Have the Capability to Restore Themselves—We must be able to recognize these situations.

"Each stream," says Christopher Hunter, "is a whole greater than the sum of its geologic, climatic, hydrologic, and biologic parts." Those who would save rivers must first see each river whole, as a separate, vital, and unique group of elements and energies that constantly seeks its own dynamic equilibrium (from Nick Lyons, Foreword to Better Trout Habitat: A Guide to Stream Restoration and Management*; Hunter 1991). It is this almost living quality of streams, along with the capability to repair and sustain themselves with the removal of disturbances, that this document must convey to the reader. This document addresses the need within agencies for a comprehensive restoration context, an appreciation of the importance of removing key disturbances to allow streams to restore themselves, and to better determine those circumstances when active intervention in the restoration process is the preferred alternative.*

corridor, and stream. In all likelihood, restoration will not involve returning a system to its pristine or original condition. The goal should be to establish self-sustaining stream functions.

Because this document may be a primary reference on ecological restoration for many users, it is appropriate that more than one definition of restoration be included. The following definition of restoration has been adopted by the Society for Ecological Restoration (SER). "Ecological restoration is the process of assisting the recovery and management of ecological integrity. Ecological integrity includes a critical range of variability in biodiversity, ecological processes, and structures, regional and historical context, and sustainable cultural practices."

Why Is a Stream Corridor Restoration Document Needed?

Interest in restoring stream corridor ecosystems is expanding nationally and internationally. Research is under way and guidelines are being developed for stream corridor restoration in both the public and private sectors. The number of case studies, published papers, technology exchanges, research projects, and symposia on both the technical and process aspects of stream corridor restoration is increasing.

Over the years, many federal agencies have contributed to this growing body of knowledge and have issued manuals and handbooks pertaining in some way to stream restoration. Much of this older literature, however, is significantly different from this document in terms of philosophy and technique. Narrow in scope and focusing on only specific aspects, regions, objectives, or treatments, it may be outdated and not reflective of new restoration techniques and philosophies. The result has been confusion and concern among both government agencies and the public on how to evaluate the need for development and implementation of restoration initiatives.

In response, this document represents an unprecedented cooperative effort by the participating federal agencies to produce a common technical reference on stream corridor restoration.

Recognizing that no two stream corridors and no two restoration initiatives are identical, this technical document broadly addresses the elements of restoration that apply in the majority of situations encountered. The document

> **It is axiomatic that no restoration can ever be perfect; it is impossible to replicate the biogeochemical and climatological sequence of events over geological time that led to the creation and placement of even one particle of soil, much less to exactly reproduce an entire ecosystem. Therefore, all restorations are exercises in approximation and in the reconstruction of naturalistic rather than natural assemblages of plants and animals with their physical environments.**
>
> *— Berger 1990*

is not a set of guidelines that cover every possible restoration situation, but it does provide a framework in which to plan restoration actions and alternatives.

What Does the Document Cover?

This document takes a more encompassing approach to restoration than most other texts and manuals. It provides broadly applicable guidance for common elements of the restoration process, but also provides alternatives, and references to alternatives, which may be appropriate for site-specific restoration activities. Moreover, the document incorporates and reflects the experiences of the collaborating agencies and provides a common technical reference that can be used to restore systems based on experiences and basic scientific knowledge.

As a general goal, this document promotes the use of ecological processes (physical, chemical, and biological) and minimally intrusive solutions to restore self-sustaining stream corridor func-

(a)

(b)

Fig. I.3: Stream corridor restoration can be applied in both (a) urban and (b) rural settings. *No matter the setting, vegetation and soil characteristics in the corridor differ distinctly from the surrounding uplands.*

The document is intended primarily for interdisciplinary technical and managerial teams and individuals responsible for planning, designing, and implementing stream corridor restoration initiatives.

tions. It provides information necessary to develop and select appropriate alternatives and solutions, and to make informed management decisions regarding valuable stream corridors and their watersheds. In addition, the document recognizes the complexity of most stream restoration work and promotes an integrated approach to restoration. It supports close cooperation among all participants in order to achieve a common set of objectives.

The guidance contained in this document is applicable nationwide in both urban and rural settings. The material presented applies to a range of stream types, including intermittent and perennial streams of all sizes, and rivers too small to be navigable by barges. It offers a scientific perspective on restoration work ranging from simple to complex, with the level of detail increasing as the scale moves from the landscape to the stream reach.

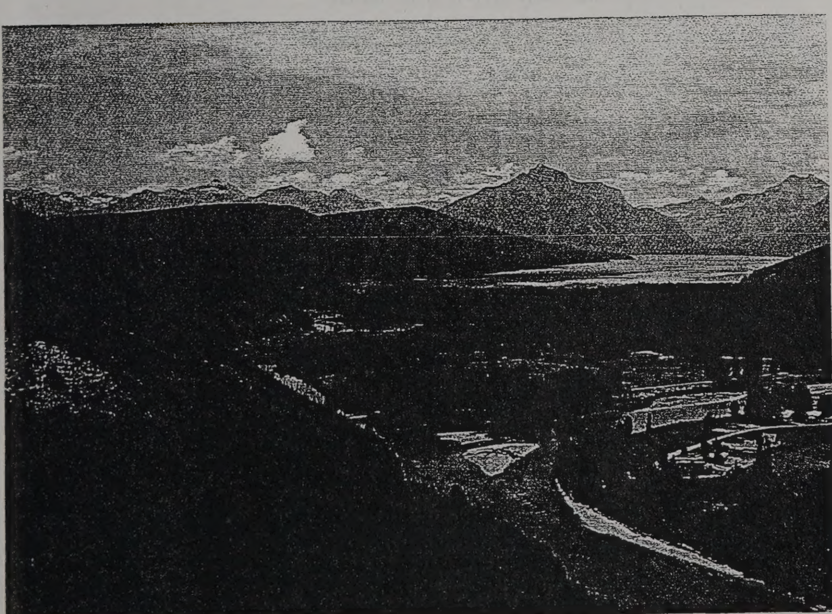


*Fig. I.4: **A stream corridor.** The document provides an overview of stream corridor structure and functions.*

Note that there are several things that this document is not intended to be.

- It is not a cookbook containing prescribed "recipes" or step-by-step instructions on how to restore a stream corridor.
- While this document refers to issues such as nonpoint source pollution and best management practices, wetlands restoration and delineation, lake and reservoir restoration, and water quality monitoring, it is not meant to focus on these subjects.
- It is not a policy-setting document. No contributing federal agency is strictly bound by its contents. Rather, it suggests and promotes a set of approaches, methods, and techniques applicable to most stream corridor restoration initiatives encountered by agencies and practitioners.
- It is not intended to be an exhaustive research document on the subject of stream corridor restoration. It does provide, however, many references for those desiring a deeper understanding of the principles and theories underlying techniques and issues discussed in general terms.

Who Is the Intended Audience?

The document is intended primarily for interdisciplinary technical and managerial teams and individuals responsible for planning, designing, and implementing stream corridor restoration initiatives. The document may also be useful to others who are working in stream corridors, including contractors, landowners, volunteers, agency staff, and other practitioners.

How Is the Document Organized?

The document is organized to provide an overview of stream corridors, steps in restoration plan development, and guidelines for implementing restoration.

The document has been divided into three principal parts. *Part I* provides background on the fundamental concepts of stream corridor structure, processes, functions, and the effects of disturbance. *Part II* focuses on a general restoration plan development process comprised of several fundamental steps. *Part III* examines the information presented in Parts I and II to consider how it can be applied in a restoration initiative.

Because of the size and complexity of the document, two features are used to assist the reader to maintain a clear orientation within the document. These features will allow the reader to more easily apply the information to specific aspects of a stream corridor restoration initiative. These features are:

- Chapter dividers that include major chapter sections and reader preview and review questions for each chapter. Table I.1 presents a summary of these questions by chapter.
- Short chapter summaries included at the beginning and end of each chapter that explain where the readers have been, where they are in the document, and where they are going.

A special emphasis has been placed on document orientation due to the special mission that the document has to fulfill. The document audience will include readers from many different technical backgrounds and with various levels of training. The orientation features have been included to reinforce the comprehensive and interdisciplinary perspective of stream corridor restoration.

How Is the Document Intended to Be Used?

Use of the document mostly depends on the goals of the reader. To begin with, a quick overview of the material is suggested prior to more thorough reading. A reader seeking only a general understanding of the principles of stream restoration may skip over some of the technical details in the body of the document. Use of document sections, chapters, and headings allows each reader to readily identify whether fur-

Agencies Contributing to This Document

- *United States Department of Agriculture:*
  - *Agricultural Research Service*
  - *Cooperative State Research, Education, and Extension Service*
  - *Forest Service*
  - *Natural Resources Conservation Service*
- *United States Department of Commerce:*
  - *National Oceanic and Atmospheric Administration*
    - *National Marine Fisheries Service*
- *United States Department of Defense:*
  - *Army Corps of Engineers*
- *United States Department of Housing and Urban Development*
- *United States Department of the Interior:*
  - *Bureau of Land Management*
  - *Bureau of Reclamation*
  - *Fish and Wildlife Service*
  - *United States Geological Survey*
  - *National Park Service*
- *United States Environmental Protection Agency*
- *Federal Emergency Management Agency*
- *Tennessee Valley Authority*

ther, more detailed reading on a subject will serve his or her purposes.

The reader is urged to recognize the interdisciplinary and technical nature of stream restoration. While some technical material may, on the surface, appear irrelevant, it may in fact be highly relevant to a specific part of the process of restoring a stream corridor.

Stream corridor restoration technologies and methodologies are evolving rapidly. Readers are encouraged to add their own notes on restoration and to make the document more relevant to local needs (e.g., a list of suitable native plant species for streambank revegetation).

This document is being published in a notebook form to allow insertion of:

- Updated material that will be made available at the Internet sites printed in the *Preface*.
- Addition of regional or locally relevant materials collected by the reader.

A Note About Units of Measurement

Metric units are commonly used throughout the world, but most data published in the United States are in English units. Although adoption of the metric system is on the increase in the United States—and for many federal agencies this conversion is mandated and being planned for—restorers of stream corridors will continue to use data that are in either metric or English units.

Appendix B contains a table of metric to English unit conversion factors, in case a unit conversion is needed.

Feedback

Readers are encouraged to share their restoration experiences and provide feedback. They can do so by accessing the Stream Corridor Restoration home page on the Internet address printed in the Preface*. Other sources of information may also be found by exploring the cooperating agencies' home pages on the Internet.*

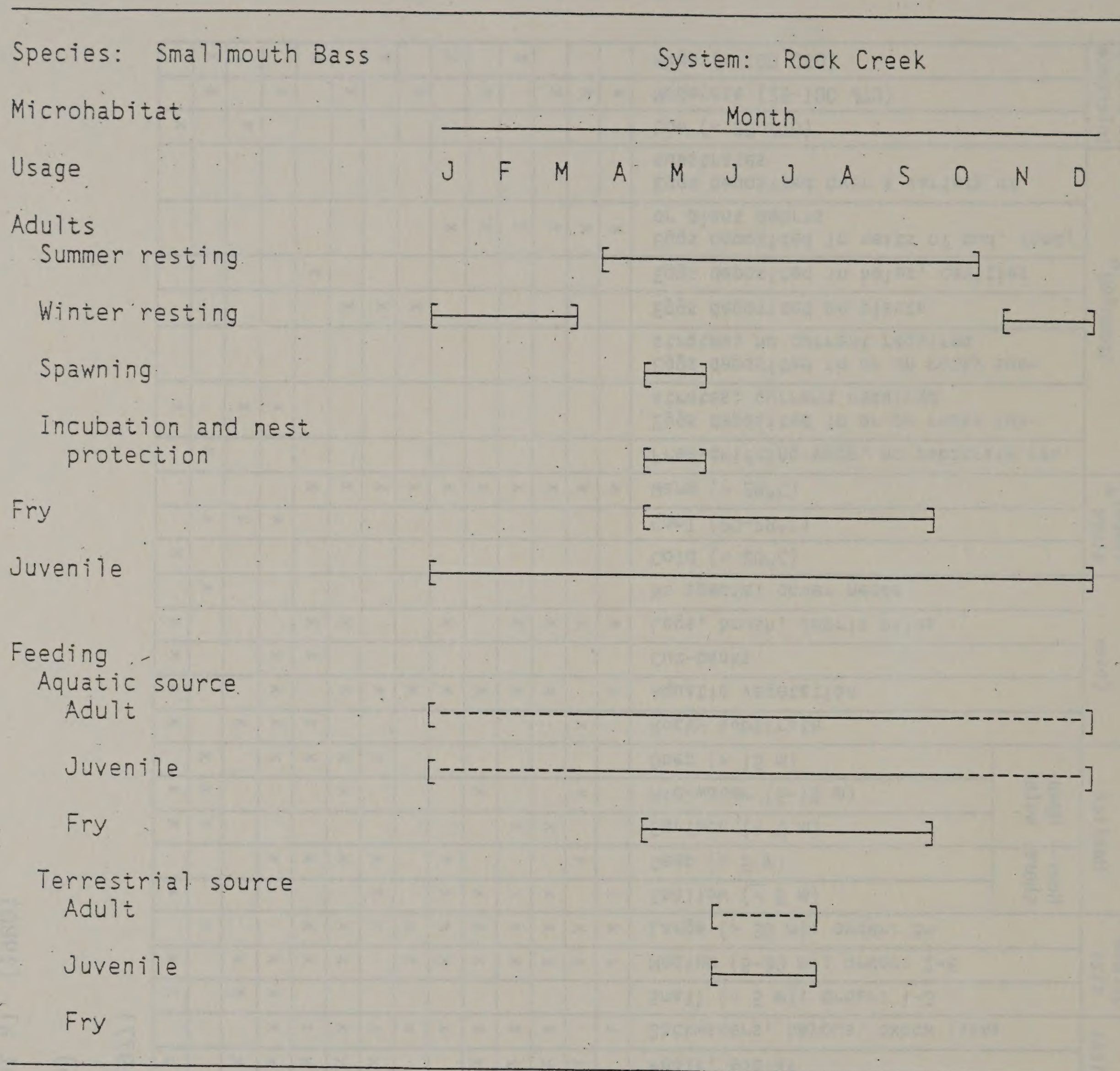
Species[c]	Riverine						Lacustrine																						
	Habitat			Stream size			Habitat					Cover					Temperature[a]			Spawning[b]							Turbidity tolerance		
							Near-shore		Open-water																				
	Riffles, runs	Pools, eddies	Backwaters, bayous, oxbow lakes	Small (< 5 m); order: 1-3	Medium (5-30 m); order: 2-6	Large (> 30 m); order: 5+	Shallow (≤ 5 m)	Deep (> 5 m)	Surface (< 5 m)	Mid-water (5-15 m)	Deep (> 15 m)	Rocky substrate	Aquatic vegetation	Cut-banks	Logs, brush, debris piles	No special cover needs	Cold (< 20°C)	Cool (20-28°C)	Warm (> 28°C)	Free-drifting eggs, no substrate req.	Eggs deposited in or on rocky substrates; current required	Eggs deposited in or on rocky substrates; no current required	Eggs deposited on plants	Eggs deposited in holes, cavities	Eggs deposited in nests of mud, sand, or plant debris	Eggs deposited over a variety of substrates	Low (< 25 JTU)	Moderate (25-100 JTU)	High (> 100 JTU)
Largemouth bass			X		X	X	X						X		X				X						X			X	
Spotted bass		X			X	X		X		X		X			X				X						X			X	
Black crappie		X	X		X	X	X		X				X		X				X						X			X	
White crappie		X	X		X	X	X		X				X		X				X						X				X
Bluegill		X	X		X	X	X			X			X						X						X			X	
Warmouth			X		X	X	X	X					X		X				X						X				X
Slough darter			X		X	X							X						X				X					X	
Common carp		X	X			X	X	X			X		X						X				X						X
Smallmouth buffalo	X	X	X		X	X		X		X	X		X		X				X				X					X	
Channel catfish	X	X	X		X	X		X			X	X		X	X				X					X					X
White sucker		X	X	X	X			X			X	X	X	X				X			X							X	
Northern hogsucker	X	X		X	X							X						X			X						X		
Striped bass	X					X			X	X	X					X		X		X								X	X
Rainbow trout	X	X		X	X		X		X	X		X	X	X	X		X				X						X		

[a]Categories from Hokanson (1977)

[b]Categories from Balon (1975)

[c]Common names from Robbins et al. (1980)

Sample species classification using guilding criteria.



Sample species periodicity chart for smallmouth bass.

Biological Services Program

HABITAT SUITABILITY INDEX MODELS: CUTTHROAT TROUT

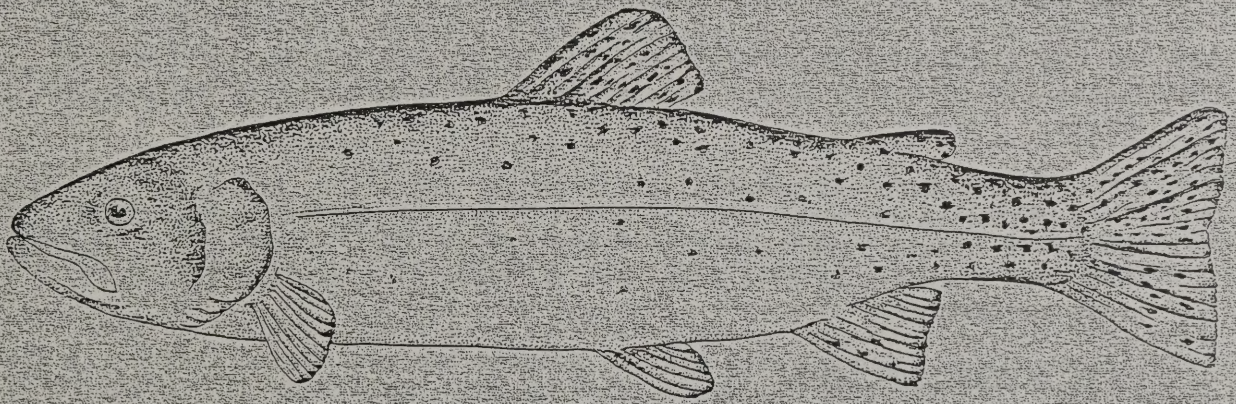
Fish and Wildlife Service

U.S. Department of the Interior

Biological Services Program

FWS/OBS-82/10.5
FEBRUARY 1982

HABITAT SUITABILITY INDEX MODELS: CUTTHROAT TROUT



Fish and Wildlife Service

U.S. Department of the Interior

CUTTHROAT TROUT (Salmo clarki)

HABITAT USE INFORMATION

General

Cutthroat trout, Salmo clarki, are a polytypic species consisting of several geographically distinct forms with a broad distribution and a great amount of genetic diversity (Hickman 1978; Behnke 1979). Behnke (1979) recognized 13 extant subspecies: Coastal cutthroat (S. c. clarki) in coastal streams from Prince William Sound, Alaska to the Eel River in California; mountain cutthroat (S. c. alpestris) in upper Columbia and Fraser River drainages of British Columbia; west slope cutthroat (S. c. lewisi) in the upper Columbia, Salmon, Clearwater, South Saskatchewan and upper Missouri drainages of Montana and Idaho; an undescribed subspecies in the Alvord basin, Oregon; Lahonton cutthroat (S. c. henshawi), Pauite cutthroat (S. c. seleniris), and an undescribed subspecies in the Humboldt River drainage of the Lahontan basin of Nevada and California; Yellowstone cutthroat (S. c. bouvieri) in the Yellowstone drainage of Wyoming and Montana and the Snake River drainage of Wyoming, Idaho, and Nevada; an undescribed subspecies (fine spotted) in the upper Snake River, Wyoming; Bonneville cutthroat (S. c. utah) in the Bonneville basin in Utah, Nevada, Idaho, and Wyoming; Colorado River cutthroat (S. c. pleuriticus) in the Colorado River drainage in Wyoming, Utah, New Mexico, and Colorado; greenback cutthroat (S. c. stomias) in the South Platte and Arkansas River systems; and Rio Grande cutthroat (S. c. virginalis) in the Rio Grande River drainage of Colorado and New Mexico. Many of these 13 subspecies are included on Federal or State endangered or threatened species lists.

Temperature and chemical preferences, migration, and other ecological and life history attributes vary among cutthroat subspecies (Behnke 1979). Differences in growth rate (Carlander 1969; Scott and Crossman 1973; Behnke 1979) and food preferences have also been reported (Trojnar and Behnke 1974) between some subspecies.

Age, Growth, and Food

Most male cutthroat trout mature at ages II to III, whereas females usually mature a year later (Irving 1954; Drummond and McKinney 1965; Johnston and Mercer 1977). In Washington streams that contain anadromous populations of cutthroat, which predominantly smolt at age II, less than 15% of the cutthroat returning to the river for the first time are sexually mature females (Mercer and Johnston 1978). The maximum life expectancy for coastal cutthroat is about 10 years (Johnston and Mercer 1976), whereas the maximum reported age for interior cutthroat is 7 years (Behnke 1979). Size at maturity will vary depending on environmental conditions. Cutthroat mature at a smaller size in small headwater streams (Behnke and Zarn 1976).

Trout are opportunistic feeders (Behnke and Zarn 1976), but their diet consists mainly of aquatic insects (Allen 1969; Carlander 1969; Baxter and Simon 1970; Scott and Crossman 1973; Griffith 1974). Other foods, such as zooplankton (McAfee 1966; Carlander 1969; Trojnar and Behnke 1974), terrestrial

insects (Carlander 1969; Trojnar and Behnke 1974; Hickman 1977), and fish (Carlander 1969) are locally or seasonally important. Cutthroat trout usually become more piscivorous as they increase in size (McAfee 1966; Carlander 1969; Baxter and Simon 1970).

Reproduction

Cutthroat trout are stream spawners. The fertilized ova are deposited in redds constructed primarily by the female in the stream gravels (Smith 1941, 1947). Spawning begins in spring, as early as February (Behnke 1979), but can occur as late as August in colder areas (Juday 1907; Fleener 1951). The time of spawning depends on water temperature, runoff (Lea 1968), ice melt (Calhoun 1944), elevation and latitude (Behnke and Zarn 1976).

Anadromy

Coastal cutthroat are the most abundant of the thirteen recognized cutthroat subspecies and consist of both resident and anadromous populations. Both populations are usually found in the same watershed. The resident populations are frequently, but not always, segregated from the anadromous stock by some barrier to anadromy. Although resident and anadromous populations have been reported to occur in sympatry in streams and lakes, more information is needed to determine if gene flow between populations is absent (Johnston 1979).

Anadromous coastal cutthroat spend less time in saltwater than steelhead trout or salmon. Although some cutthroat overwinter in saltwater, most return to freshwater after 3 to 8 months (Johnston 1979). During this period in saltwater, the cutthroat stay close to shore and are rarely found at depths greater than 3 m. Preferred habitats in saltwater are gravel beaches vegetated above the high tide mark and gravel spits created by tidal currents. Cutthroat are rarely found in saltwater in areas with silt, mud, or solid rock substrate. Anadromous cutthroat utilize cover during upstream migration from saltwater.

Coastal cutthroat initially smolt at age II, III, or IV. Some smolt at age I, whereas others may not migrate to salt water until age VI (Jones 1974, 1975, 1976). In Washington, the smallest cutthroat entering salt water weigh from 25 to 45 gms and are 120 to 170 mm long. Physiological adaptation to salt water appears to be related to size rather than age (Johnston and Mercer 1976).

In Washington and Oregon, smolt movement to salt water begins in March, peaks in mid-May, and is completed by mid-June (Johnston and Mercer 1976). In Alaska, migration begins in April (Armstrong 1971; Jones 1974, 1975, 1976), peaks at the end of May, but may continue into August. Most seaward migrations occur at night. Re-entry into fresh water in Washington and Oregon begins in July, peaks in September and October, and lasts until the end of October (Giger 1972; Johnston and Mercer 1976). In smaller coastal streams, re-entry begins in October, peaks in December and January, and continues into March. Migrations into small stream-lake systems in Alaska begin as early as mid-May, peak in September, and last until October (Armstrong 1971; Jones 1974, 1975, 1976).

Specific Habitat Requirements

Optimal cutthroat trout riverine habitat is characterized by clear, cold water; a silt free rocky substrate in riffle-run areas; an approximately 1:1 pool-riffle ratio with areas of slow, deep water; well vegetated stream banks; abundant instream cover; and relatively stable water flow, temperature regimes, and stream banks (Raleigh and Duff 1981). Cutthroat trout tend to occupy headwater stream areas, especially when other trout species are present in the same river system (Glova and Mason 1976).

Optimal lacustrine habitat is characterized by clear, cold, deep lakes that are typically oligotrophic, but may vary in size and chemical quality, particularly in reservoir habitats. Cutthroat trout are stream spawners and require tributary streams with gravel substrate in riffle areas for reproduction to occur.

Trout literature does not clearly distinguish between feeding stations, escape cover, and winter cover requirements. Prime requisites for optimal feeding stations appear to be low water velocity and access to a plentiful food supply, e.g., energy accretion at a low energy cost. Water depth is not clearly defined as a selection factor, and overhead cover is preferred but not essential. Escape cover, however, must be nearby (Raleigh and Duff 1981). The feeding stations of dominant adult trout will include overhead cover when available. The feeding stations of subdominant adults and juveniles, however, may not always include overhead cover.

Cover is recognized as one of the essential components of trout streams. Boussu (1954) was able to increase the number and weight of trout in stream sections by adding artificial brush cover and to decrease numbers and weight by removing brush cover and undercut banks. Lewis (1969) reported that the amount of cover was important in determining the number of trout in sections of a Montana stream. Cover for adult trout consists of areas of obscure stream bottom in areas of water $\geq$ 15 cm deep with a low velocity of $\leq$ 15 cm/sec (Wesche 1980). Wesche (1980) reported that, in larger streams, the abundance of trout $\geq$ 15 cm in length increased with depth; most were at depths of at least 15 to 45 cm. Cover is provided by overhanging vegetation; submerged vegetation; undercut banks; instream objects, such as debris piles, logs, large rocks; and pool depth or surface turbulence (Giger 1973). A cover area of $\geq$ 25% of the total stream area will provide adequate cover for adult trout; a cover area of $\geq$ 15% is adequate for juveniles. The main use of summer cover is probably for predator avoidance and resting. In winter, salmonids occupy different habitat areas than in the summer (Hartman 1965; Everest 1969; Bustard and Narver 1975a).

In some streams, the major factor limiting salmonid densities may be the amount of adequate overwintering habitat rather than summer rearing habitat (Bustard and Narver 1975a). Winter hiding behavior in salmonids is triggered by low temperatures (Chapman and Bjornn 1969; Everest 1969; Bustard and Narver 1975a,b). Cutthroat trout were found under boulders, log jams, upturned roots, and debris when temperatures neared 4 to 8° C, depending on velocity (Bustard and Narver 1975a). Everest (1969) found juvenile rainbows 15 to 30 cm deep in the substrate, which was often covered by 5 to 10 cm of anchor

ice. Lewis (1969) reported that, during winter, adult rainbow trout tended to move into deeper water (class 1 pools). Bjornn (1971) indicated that downstream movement during or preceding winter did not occur if sufficient winter cover was locally available. Trout move to winter cover to avoid physical damage from ice scouring (Hartman 1965; Chapman and Bjornn 1969) and to conserve energy (Chapman and Bjornn 1969; Everest 1969).

Headwater trout streams are relatively unproductive. Most energy inputs to the stream are in the form of allochthonous materials, such as terrestrial vegetation and terrestrial insects (Idyll 1942; Chapman 1966; Hunt 1975). Aquatic invertebrates are most abundant and diverse in riffle areas with rubble substrate and on submerged aquatic vegetation (Hynes 1970). However, optimal substrate for maintenance of a diverse invertebrate population consists of a mosaic of gravel, rubble, and boulders with rubble being dominant. The invertebrate fauna is much more abundant and diverse in riffles than in pools (Hynes 1970), but a ratio of about 1:1 of pool to riffle area (about 40 to 60% pool area) appears to provide an optimal mix of trout food producing and rearing areas. In riffle areas, the presence of fines (> 10%) reduces the production of invertebrate fauna (based on Cordone and Kelly 1961; Crouse et al. 1981).

Canopy cover is important in maintaining shade for stream temperature control and in providing allochthonous materials to the stream. Too much shade, however, can restrict primary productivity in a stream. Stream temperatures can be increased or decreased by controlling the amount of shade. About 50 to 75% mid-day shade appears optimal for most small trout streams (Anonymous 1979). Shading becomes less important as stream gradient and size increases. In addition, a well vegetated riparian area helps to control watershed erosion. In most cases, a buffer strip about 30 m deep, 80% of which is either well vegetated or has stable rocky stream banks, will provide adequate erosion control and maintain undercut stream banks characteristic of good trout habitat. The presence of fines in riffle-run areas can adversely affect embryo survival, food production and cover for juveniles.

There is a definite relationship between the annual flow regime and the quality of trout habitat. The most critical period is typically the base flow (lowest flows of late summer to winter). A base flow ≥ 50% of the average annual daily flow is considered excellent, a base flow of 25 to 50% is considered fair, and a base flow of < 25% is considered poor for maintaining quality trout habitat (adapted from Binns and Eiserman 1979; Wesche 1980).

Of 66 streams sampled in British Columbia, those containing cutthroat trout had a pH of 6.0 to 8.8 (Hartman and Gill 1968). Thirteen streams in Wyoming containing populations of Colorado River cutthroat trout had pH levels of 7.1 to 8.3 (Binns 1977). Sekulich (1974) reported that the pH in three reservoirs containing cutthroat trout ranged from 7.8 to 8.5. Platts (1974) analyzed three streams in Idaho with cutthroat trout where the pH ranged from 7.3 to 7.9 and total dissolved solids ranged from 41 to 63 mg/l. Some isolated populations of cutthroat trout in the Great Basin area have developed a unique tolerance for high pH, alkalinity, total dissolved solids, and temperature conditions. The Lahontan basin cutthroat trout persist in Pyramid and Walker Lakes, Nevada, where total dissolved solids exceed 5,000 mg/l and 10,000 mg/l, respectively (Behnke and Zarn 1976). The largest cutthroat trout ever recorded came from Pyramid Lake, which has a pH range between 9.0 and 9.5. The Lahontan

basin cutthroat also lives in alkaline waters, such as Walker Lake, Nevada (alkalinity of 2,900 mg/l). These conditions are probably lethal to other cutthroat trouts (Behnke and Zarn 1976). Precise pH tolerance and optimal ranges for cutthroat trout are not well documented. Most cutthroat populations can probably tolerate a pH range of 5 to 9.5, with an optimal range of 6.5 to 8. The Lahontan basin cutthroat appear to have developed a tolerance to higher pH conditions, with regional pH tolerance and optimal ranges of 5 to 10 and 6.5 to 8.5, respectively.

Bachmann (1958) reported that, at turbidities above 35 ppm, cutthroat trout stopped feeding and moved to cover. Turbidities of less than 25 JTU and total dissolved solids from 38 to 544 mg/l characterized 13 Wyoming streams containing cutthroat trout (Binns 1977).

Adult. Dissolved oxygen requirements vary with species, age, prior acclimation temperature, water velocity, activity level, and concentration of substances in the water (McKee and Wolf 1963). As temperature increases, the dissolved oxygen saturation level in the water decreases while the dissolved oxygen requirements for the fish increases. As a result, an increase in temperature resulting in a decrease in dissolved oxygen can be detrimental to the fish. Optimal oxygen levels for cutthroat trout are not well documented, but appear to be > 7 mg/l at temperatures ≤ 15° C and ≥ 9 mg/l at temperatures > 15° C. Doudoroff and Shumway (1970) demonstrated that swimming speed and growth rates for salmonids declined with decreasing dissolved oxygen levels. At temperatures ≥ 15° C, cutthroat trout generally avoid water with dissolved oxygen levels of less than 5 mg/l (Trojnar 1972; Sekulich 1974).

Cutthroat trout usually do not persist in waters where maximum temperatures consistently exceed 22° C, although they may be able to withstand brief periods of water temperature as high as 26° C if considerable nightime cooling takes place (Behnke and Zarn 1976). The Humboldt River cutthroat trout in the Lahontan basin, however, occupy waters where temperatures may reach a summer maximum of 25° C (Behnke 1979). Needham and Jones (1959) reported cutthroat trout actively feeding at 0° C. Bell (1973) reported a preferred temperature range of 9 to 12° C for cutthroat trout. Dwyer and Kramer (1975) reported the greatest scope for activity in cutthroat trout occurred at 15° C when tested at 5° C increments. We assume that scope for activity is a better measure of optimal temperature than temperature preference tests and have selected 12-15° C as an optimal temperature range for cutthroat trout.

Focal point velocities for adult cutthroat trout on territorial stations in Idaho streams were primarily between 10 and 14 cm/sec, with a maximum of 22 cm/sec (Griffith 1972).

Embryo. Incubation time varies inversely with temperature. Eggs usually hatch within 28 to 40 days (Cope 1957), but may take as long as 49 days (Scott and Crossman 1973). Bell (1973) reported that cutthroat trout spawning temperatures ranged from 6 to 17° C. The optimal temperature for embryo incubation is approximately 10° C (Snyder and Tanner 1960). Calhoun (1966) reported increased mortalities of rainbow embryos at temperatures < 7° C and normal development at temperatures ≤ 12° C. Hooper (1973) and Thompson (1972) reported spawning velocities ranging from 31 to 92 cm/sec, while Hunter (1973) reported the range as 11 to 40 cm/sec. Average water column velocities for embryo development apparently range from 11 to 92 cm/sec. We assume that

optimal velocities range from 30 to 60 cm/sec. The combined effects of temperature, dissolved oxygen levels, water velocity, and gravel permeability are important for successful incubation (Coble 1961). In a 30% sand and 70% gravel mixture, only 28% of implanted steelhead embryos hatched; of the 28% that hatched, only 74% emerged (Bjornn 1969; Phillips et al. 1975). We assume that these same results would be true for the closely related cutthroat trout. We further assume that optimal spawning gravel conditions include ≤ 5% fines, and that ≥ 30% fines will cause low survival of embryos and emerging yolk-sac fry. Suitable incubation substrate is gravel 0.3 to 8 cm in diameter (Duff 1980). Optimal substrate size will depend on size of spawners, but we assume it will average 1.5 to 6.0 cm in diameter. Doudoroff and Shumway (1970) reported that salmonids incubated at low dissolved oxygen levels were weak and small with slower development and more abnormalities. Dissolved oxygen requirements for cutthroat trout embryos are probably similar to the requirements for adults.

Fry. Cutthroat trout remain in the gravel for about two weeks after hatching (Scott and Crossman 1973) and emerge 45 to 75 days after egg fertilization, depending on water temperature (Calhoun 1944; Lea 1968). When moving from natal gravels to rearing areas, cutthroat trout fry exhibit three distinctly different genetically controlled patterns: 1) downstream to a larger river or lake; 2) upstream from an outlet river to a lake; or 3) local dispersion within a common spawning and rearing area to areas of low velocity and cover (Raleigh and Chapman 1971). Fry of lake resident fish may either move into the lake from natal streams during the first growing season or overwinter in the spawning stream and move into the lake during subsequent growing seasons (Raleigh 1971; Raleigh and Chapman 1971). Salmo clarki lewisi average two growing seasons, but may spend 1 to 4 years in the stream before migrating to the lake (Roscoe 1974).

Fry residing in streams prefer shallower water and slower velocities than other life stages (Miller 1957; Horner and Bjornn 1976). Fry utilize velocities of less than 30 cm/sec, but less than 8.0 cm/sec are preferred (Griffith 1972; Horner and Bjornn 1976). Fry survival decreases with increased velocity after optimal velocity has been reached (Bulkley and Benson 1962; Drummond and McKinney 1965). A pool area of 40% to 60% of the total stream area is assumed to provide optimal fry habitat. Cover in the form of aquatic vegetation, debris piles, and the interstitial spaces between rocks is critical. Griffith (1972) states that younger trout live in shallower water and stay closer to escape cover than do older trout. Few fry are found more than 1 m from cover. As the young cutthroat grow, they move to deeper, faster water. Everest (1969) suggested that one reason for this movement was the need for cover, which is provided by increased water depth, surface turbulence, and larger substrate.

Trout fry usually overwinter in shallow areas of low velocity near the stream margin, with rubble being the principle cover (Bustard and Narver 1975a). Optimal size of substrate used as winter cover by steelhead fry and small juveniles ranges from 10 to 40 cm in diameter (Hartman 1965; Everest 1969). An area of substrate of this size class (10-40 cm) of ≥ 10% of the total habitat will probably provide adequate cover for cutthroat fry and small juveniles. The use of smaller diameter rocks (gravel) for winter cover may result in increased mortality due to greater shifting of the substrate (Bustard

and Narver 1975a). The presence of fines (≥ 10%) in the riffle-run areas impairs the value of the area as cover for fry and small juveniles.

Juvenile. Juvenile cutthroat trout in streams are most often found in water depths of 45 to 75 cm and velocities of 25 to 50 cm/sec (Nickelson unpublished data). Griffith (1972) reported focal point velocities for juvenile cutthroat in Idaho of between 10 and 12 cm/sec, with a maximum velocity of 22 cm/sec. Metabolic rates are highest between 11 and 21° C with an apparent optimal temperature of 15° C (Dwyer and Kramer 1975).

Bustard and Narver (1975b) demonstrated that juvenile cutthroat trout used rubble and overhanging banks as cover. The juveniles also showed a preference for clean, as opposed to silted, rubble for cover. Common types of cover for juvenile trout are upturned roots, logs, debris piles, overhanging banks, and small boulders (Bustard and Narver 1975a). Young salmonids occupy different habitats in winter than in summer, with log jams and rubble important as winter cover. Wesche (1980) observed that larger cutthroat trout (> 15 cm long) tended to use streamside cover (overhanging banks and vegetation) more often than instream substrate objects, while juveniles (≤ 15 cm) preferred instream substrate cover.

HABITAT SUITABILITY INDEX (HSI) MODELS

Figure 1 depicts the theoretical relationships among model variables, components, and HSI for the cutthroat trout model.

Model Applicability

Geographic area. The following model is applicable over the entire range of cutthroat trout distribution. Where differences in habitat requirements have been identified for different races of cutthroat trout, suitability index graphs have been constructed to reflect these differences. For this reason, care must be excercised in use of the individual graphs and equations.

Season. The model rates the freshwater habitat of cutthroat trout for all seasons of the year.

Cover types. The model is applicable to freshwater riverine or lacustrine habitats.

Minimum habitat area. Minimum habitat area is the minimum area of continuous habitat that is required for a species to live and reproduce. Since cutthroat can move considerable distances to spawn or locate suitable summer or winter rearing habitat, no attempt has been made to define a minimum habitat size for the species.

Verification level. An acceptable level of performance for this cutthroat trout model is for it to produce an index between 0 and 1 that the authors and other biologists familiar with cutthroat trout ecology believe is positively correlated with the carrying capacity of the habitat. Model verification consisted of testing the model outputs from sample data sets developed by the authors to simulate high, medium, and low quality cutthroat trout habitat.

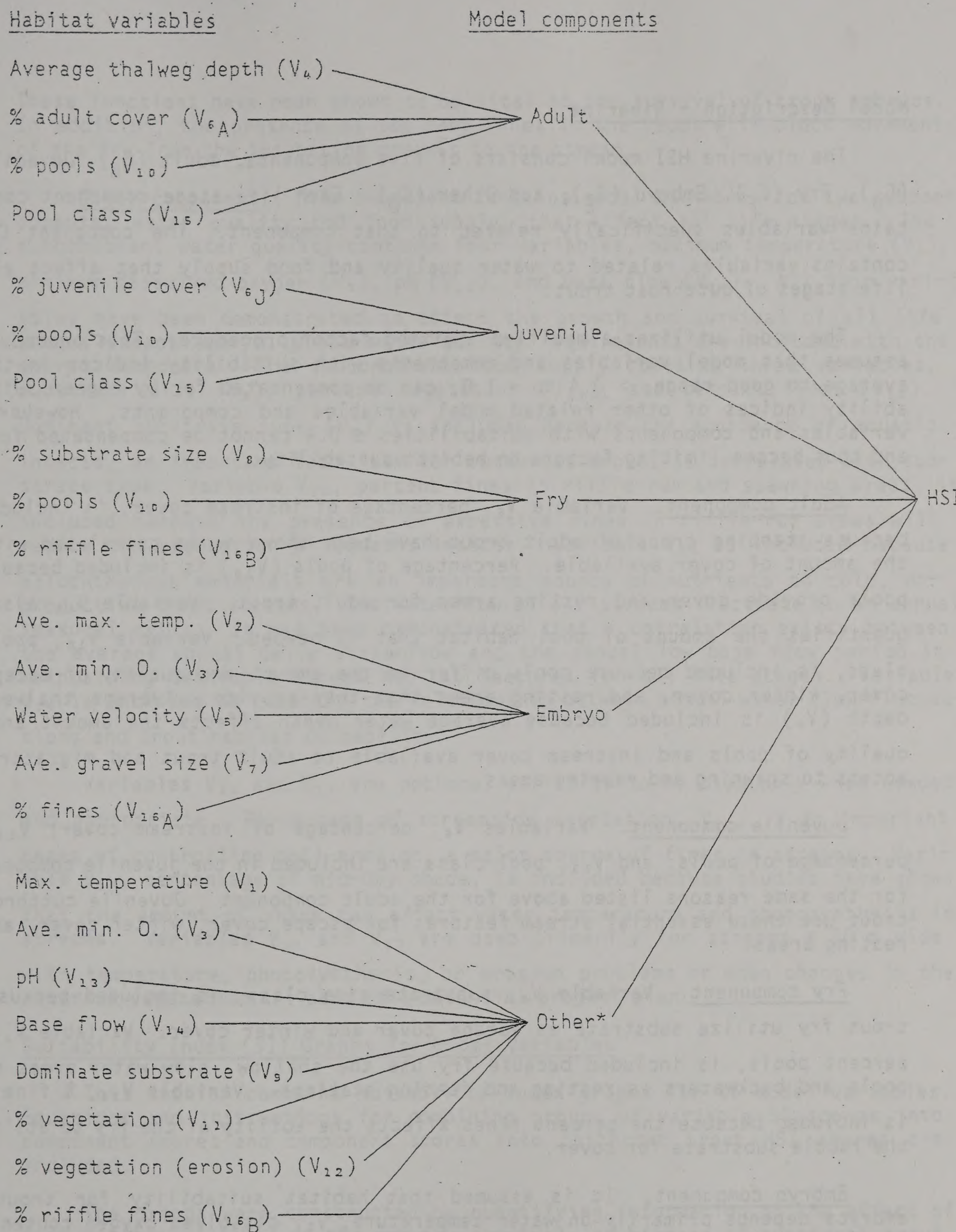


Figure 1. Diagram illustrating the relationships among model variables, components, and HSI.

Model Description - Riverine

The riverine HSI model consists of five components, adult (C_A), Juvenile (C_J), Fry (C_F), Embryo (C_E), and Other (C_O). Each life stage component contains variables specifically related to that component. The component C_O contains variables related to water quality and food supply that affect all life stages of cutthroat trout.

The model utilizes a modified limiting factor procedure. This procedure assumes that model variables and components with suitability indices in the average to good range, > 0.4 to < 1.0, can be compensated for by higher suitability indices of other related model variables and components. However, variables and components with suitabilities ≤ 0.4 cannot be compensated for, and thus become limiting factors on habitat suitability.

Adult component. Variable V_6, percentage of instream cover, is included because standing crops of adult trout have been shown to be correlated with the amount of cover available. Percentage of pools (V_{10}) is included because pools provide cover and resting areas for adult trout. Variable V_{10} also quantifies the amount of pool habitat that is needed. Variable V_{15}, pool class, is included because pools differ in the amount and quality of escape cover, winter cover, and resting areas that they provide. Average thalweg depth (V_4) is included because average water depth affects the amount and quality of pools and instream cover available to adult trout and migratory access to spawning and rearing areas.

Juvenile component. Variables V_6, percentage of instream cover; V_{10}, percentage of pools; and V_{15}, pool class are included in the juvenile component for the same reasons listed above for the adult component. Juvenile cutthroat trout use these essential stream features for escape cover, winter cover, and resting areas.

Fry component. Variable V_8, substrate size class, is included because trout fry utilize substrate as escape cover and winter cover. Variable V_{10}, percent pools, is included because fry use the shallow, slow water areas of pools and backwaters as resting and feeding stations. Variable V_{16}, % fines, is included because the percent fines affects the ability of the fry to utilize the rubble substrate for cover.

Embryo component. It is assumed that habitat suitability for trout embryos depends primarily on water temperature, V_2; dissolved oxygen content, V_3; water velocity, V_5; spawning gravel size, V_7; and percent fines, V_{16}. Water velocity, V_5; gravel size, V_7; and percent fines, V_{16}, are interrelated factors that have been shown to effect the transport of dissolved oxygen to the embryo and the removal of the waste products of metabolism from the embryo.

These functions have been shown to be vital to the survival of trout embryos. In addition, the presence of too many fines in the redds will block movement of the fry from the incubating gravels to the stream.

Other component. This component contains model variables for two subcomponents, water quality and food supply, that affect all life stages. The subcomponent water quality contains four variables, maximum temperature (V_1), minimum dissolved oxygen (V_3), pH (V_{13}), and base flow (V_{14}). All four variables have been demonstrated to affect the growth and survival of all life stages except embryo, whose water quality requirements are included with the embryo component. The subcomponent food supply contains three variables, substrate size (V_9), percent vegetation (V_{11}), and percent fines (V_{16}). Dominant substrate type (V_9) is included because the abundance of aquatic insects, an important food item for cutthroat trout, is correlated with substrate type. Variable V_{16}, percent fines in riffle-run and spawning areas, is included because the presence of excessive fines in riffle-run areas will reduce the production of aquatic insects. Variable V_{11} is included because allochthonous materials are an important source of nutrients to cold, unproductive trout streams. The waterflow of all streams fluctuate on an annual seasonal cycle. It has been demonstrated that a correlation exists between the average annual daily streamflow and the annual low base flow period in maintaining desirable stream habitat features for all life stages. Variable V_{14} is included to quantify the relationship between annual water flow fluctuations and trout habitat suitability.

Variables V_{12} and V_{17} are optional variables to be used only when needed and appropriate. Percentage of streamside vegetation, V_{12}, is an important means of controlling soil erosion, a major source of fines in streams. Variable V_{17}, percentage of mid-day shade, is included because studies have shown that the amount of shade can affect water temperature and photosynthesis in streams. Variables V_{12} and V_{17} are used primarily for streams $\leq$ 50 m wide with temperature, photosynthesis, or erosion problems or when changes in the riparian vegetation are part of a potential project plan.

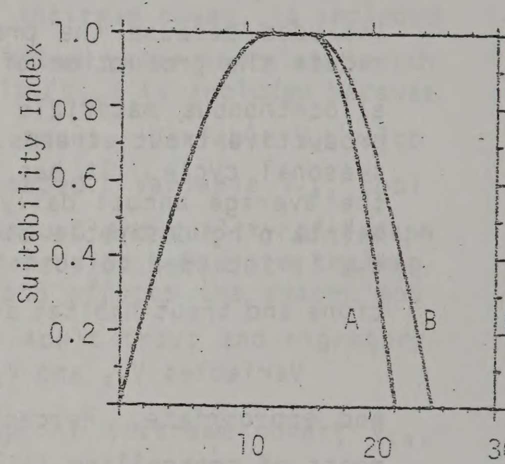
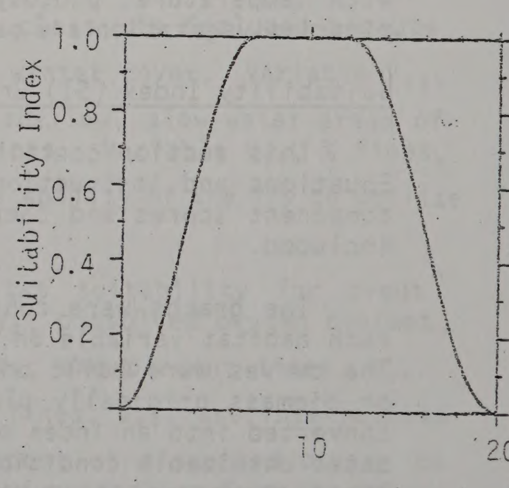
Suitability Index (SI) Graphs for Model Variables

This section contains suitability index graphs for 17 model variables. Equations and instructions for combining groups of variable SI scores into component scores and component scores into cutthroat trout HSI scores are included.

The graphs were constructed by quantifying information on the effect of each habitat variable on the growth, survival, or biomass of cutthroat trout. The curves were built on the assumption that increments of growth, survival, or biomass originally plotted on the y-axis of the graph could be directly converted into an index of suitability from 0 to 1.0 for the species; 0 indicates unsuitable conditions and 1.0 indicates optimal conditions. Graph trend lines represent the author's best estimate of suitability for the various

levels of each variable presented. The graphs have been reviewed by biologists familiar with the ecology of the species, but obviously some degree of SI variability exists. The user is encouraged to vary the shape of the graphs when existing regional information indicates that the variable suitability relationship is different.

The habitat measurements and SI graph construction are based on the premise that it is the extreme, rather than the average, values of a variable that most often limit the carrying capacity of a habitat. Thus, measurement of extreme conditions, e.g., maximum temperatures and minimum dissolved oxygen levels, are often the data used with the graphs to derive the SI values for the model. The letters R and L in the habitat column identify variables used to evaluate riverine (R) or lacustrine (L) habitats.

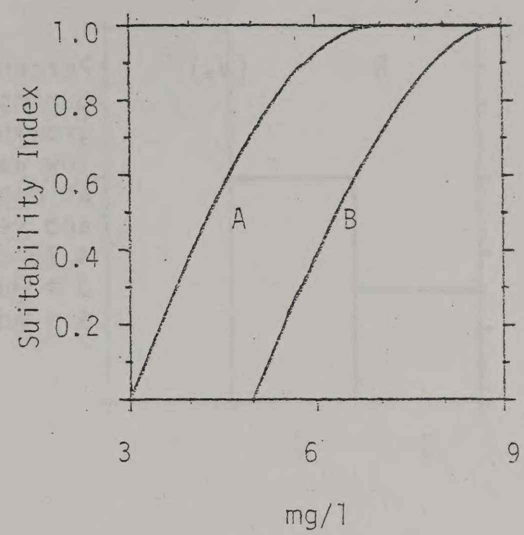
Habitat	Variable		Suitability Graph
R,L	(V_1)	Average maximum water temperature (°C) during the warmest period of the year (adult, juvenile, and fry). For lacustrine habitats, use temperature strata nearest optimal in dissolved oxygen zones of > 3 mg/l. A = General B = Lahontan Basin	
R	(V_2)	Average maximum water temperature (°C) during embryo development.	

R,L (V$_3$)

Average minimum dissolved oxygen (mg/l) during the late growing season low water period and during embryo development (adult, juvenile, fry, and embryo).

For lacustrine habitats, use the dissolved oxygen readings in temperature zones nearest to optimal where dissolved oxygen is > 3 mg/l.

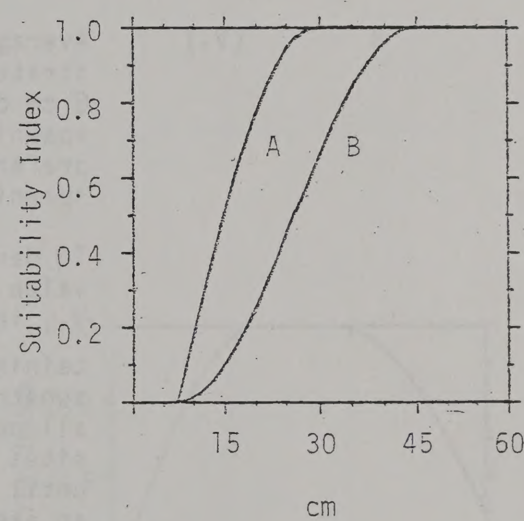
A = ≤ 15° C
B = > 15° C



R (V$_4$)

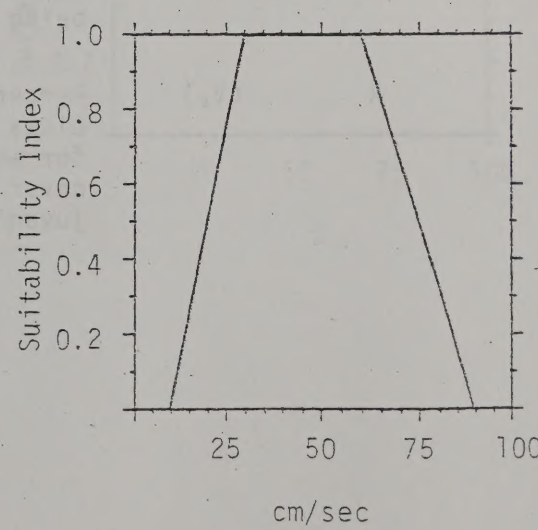
Average thalweg depth (cm) during the late growing season low water period.

A = ≤ 5 m stream width
B = > 5 m stream width

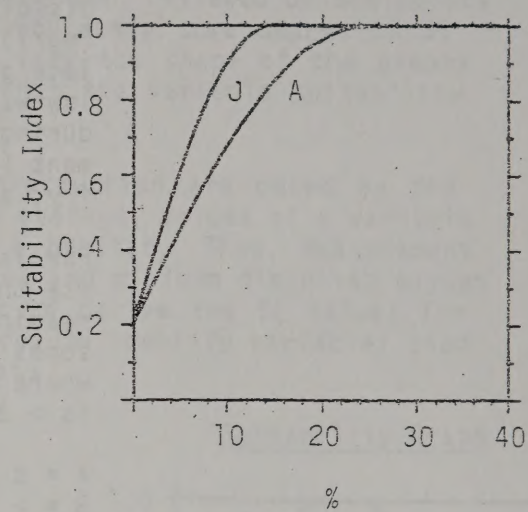


R (V$_5$)

Average velocity (cm/sec) over spawning areas during embryo development.

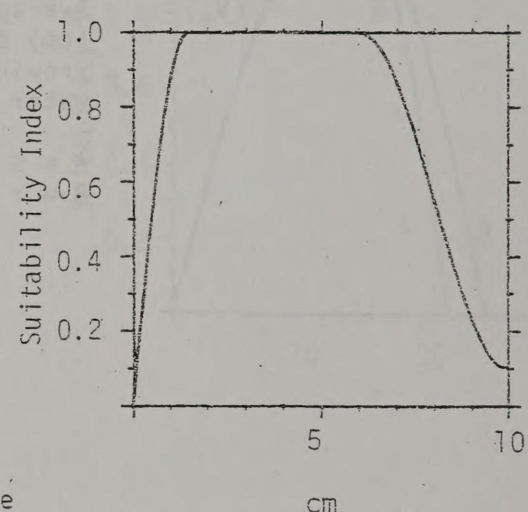


R (V6) Percent cover during the late growing season low water period at depths ≥ 15 cm and velocities < 15 cm/sec. J = Juveniles A = Adults

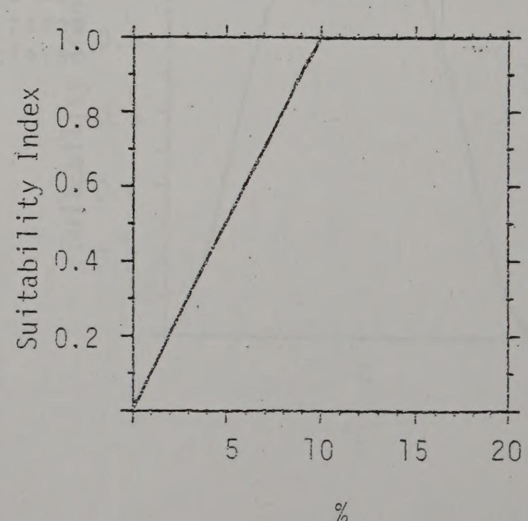


R (V7) Average size of substrate between 0.3-8 cm diameter in spawning areas, preferably during the spawning period.

To derive an average value for use with graph V7, include areas containing the best spawning substrate sampled until all potential spawning sites are included or until the sample contains an area equal to 5% of the total cutthroat habitat being evaluated.

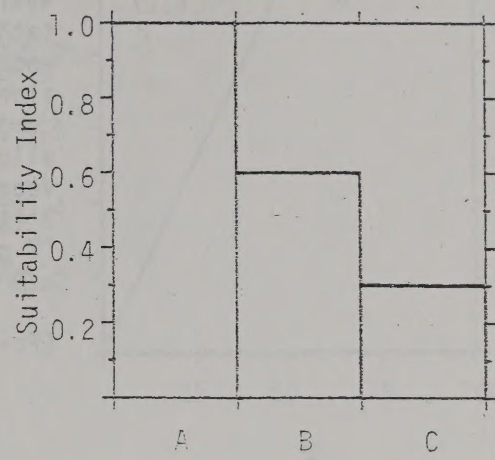


R (V8) Percent substrate size class (10-40 cm) used for winter and escape cover by fry and small juveniles.

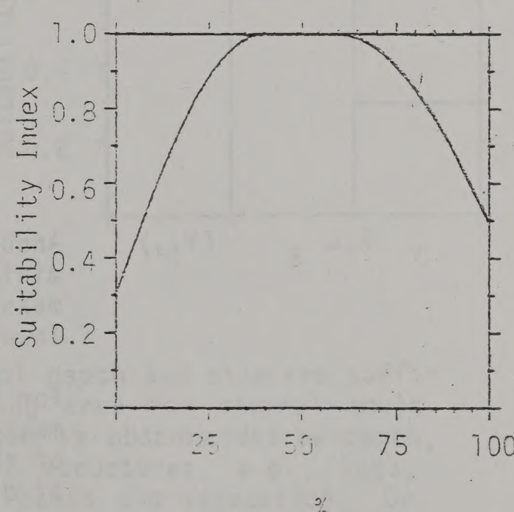


R (V$_9$) Dominant (≥ 50%) substrate type in riffle-run areas for food production.

A) Rubble or small boulders or aquatic vegetation in spring areas dominant with limited amounts of gravel, large boulders, or bedrock.
B) Rubble, gravel, boulders, and fines occur in approximately equal amounts or gravel is dominant. Aquatic vegetation may or may not be present.
C) Fines, bedrock, or large boulders are dominant. Rubble and gravel are insignificant (≤ 25%).

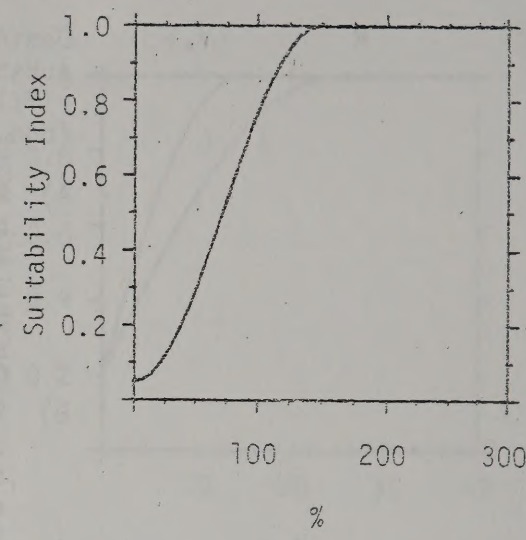


R (V$_{10}$) Percent pools during the late growing season low water period.

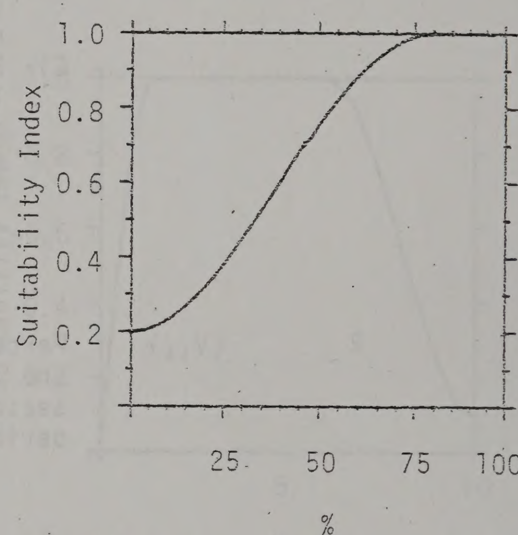


R (V$_{11}$) Average percent vegetation (trees, shrubs, and grasses-forbs) along the streambank during the summer for allochthonous input. Vegetation Index = 2 (% shrubs) + 1.5 (% grasses) + (% trees) + 0 (% bareground).

(For streams ≤ 50 m wide)



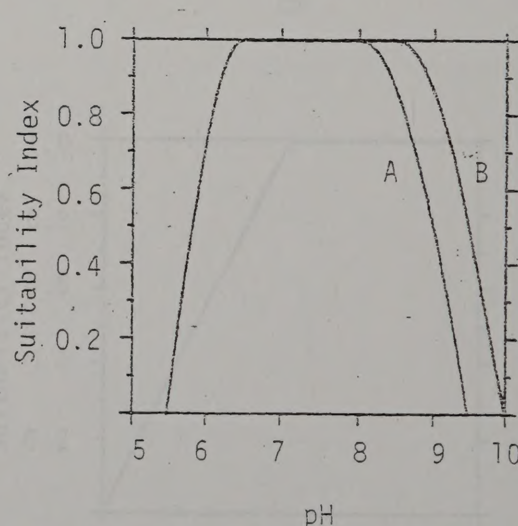
R (V$_{12}$) (Optional) Average percent rooted vegetation and stable rocky ground cover along the streambank during the summer (erosion control).



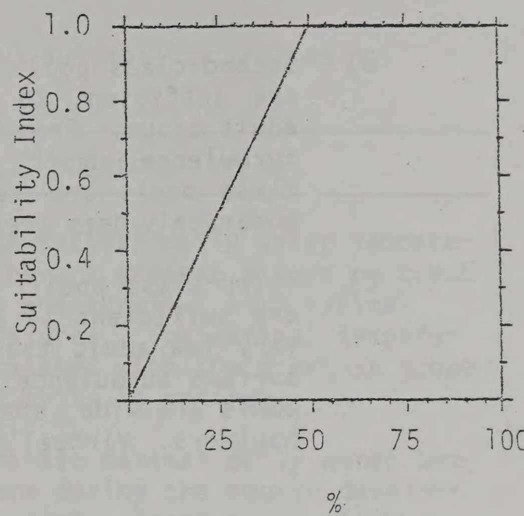
R,L (V$_{13}$) Annual maximal or minimal pH. Use the measurement with the lowest SI value.

For lacustrine habitats, measure pH in the zone of the best combination of dissolved oxygen and temperature.

A = General
B = Lahontan Basin



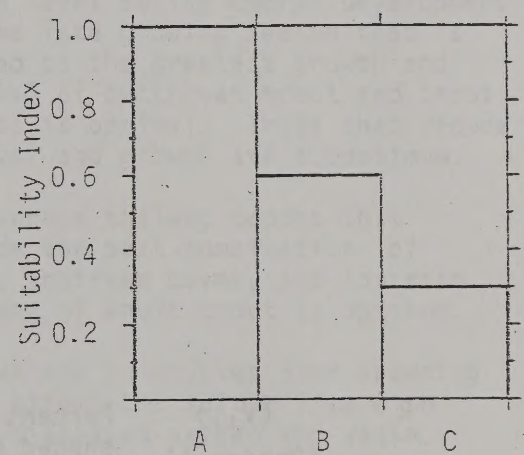
R (V_{14}) Average annual base flow regime during the late summer or winter low flow period as a percentage of the average annual daily flow.



R (V_{15}) Pool class rating during the late growing season low flow period. The rating is based on the % of the area containing pools of 3 classes as described below.

A) ≥ 30% of the area is comprised of 1st-class pools.
B) ≥ 10%-< 30% 1st-class pools or ≥ 50% 2nd-class pools.
C) < 10% 1st-class pools and < 50% 2nd-class pools.

(See pool class descriptions below)



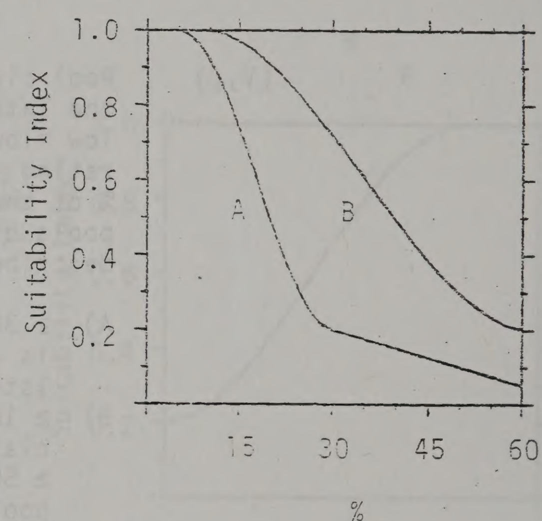
A) First-class pool: Large and deep. Pool depth and size are sufficient to provide a low velocity resting area for several adult trout. More than 30% of the pool bottom is obscure due to depth, surface turbulence, or the presence of structures, e.g., logs, debris piles, boulders, or overhanging banks and vegetation. Or, the greatest pool depth is ≥ 1.5 m in streams ≤ 5 m wide or ≥ 2 m deep in streams > 5 m wide.

B) Second-class pool: Moderate size and depth. Pool depth and size are sufficient to provide a low velocity resting area for a few adult trout. From 5 to 30% of the bottom is obscure due to surface turbulence, depth, or the presence of structures. Typical second class pools are large eddies behind boulders and low velocity, moderately deep areas beneath overhanging banks and vegetation.

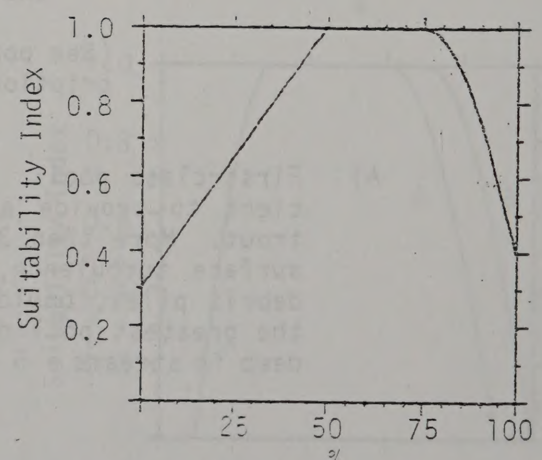
C) Third-class pool: Small or shallow or both. Pool depth and size are sufficient to provide a low velocity resting area for one to very few adult trout. Cover, if present, is in the form of shade, surface turbulence, or very limited structure. Typical third-class pools are wide, shallow pool areas of streams or small eddies behind boulders. Virtually the entire bottom area is discernable.

R (V_{16}) Percent fines (< 3 mm) in riffle-run and in spawning areas during average summer flows.

A = Spawning
B = Riffle-run



R (V_{17}) (Optional) Percent of stream area shaded between 1000 and 1400 hrs (for streams ≤ 50 m wide). Do not use on cold (<18°C) unproductive streams.



References to sources of data and the assumptions used to construct the above suitability index graphs for cutthroat trout HSI models are presented in Table 1.

Table 1. Data sources for cutthroat trout suitability indices.

	Variable and source	Assumption
V_1	Needham and Jones 1959 Bell 1973 Behnke and Zarn 1976 Behnke 1979 Dwyer and Kramer 1975	Average maximal daily water temperatures have a greater effect on trout growth and survival than minimal temperatures. The maximal temperature related with the greatest scope for activity is optimum.
V_2	Snyder and Tanner 1960 Bell 1973 Calhoun 1966	The average maximal daily water temperature during the embryo development period related to the highest survival and normal development of the embryo is optimum. Those temperatures that reduce survival are suboptimum.
V_3	Doudoroff and Shumway 1970 Trojnar 1972 Sekulich 1974	The average minimal daily dissolved oxygen level during embryo development and the late growing season that is related to the greatest growth and survival of cutthroat trout and trout embryos is optimal. Those that reduce survival and growth are suboptimum.
V_4	Delisle and Eliason 1961 Estimated by authors	The average thalweg depths that provide the best combination of pools, instream cover, and instream movement of adult trout is optimum.
V_5	Thompson 1972 Hooper 1973 Hunter 1973	The average velocities over spawning areas affect the suitability with which dissolved oxygen and waste products are carried to and from the developing embryos. Average velocities which result in the highest survival of embryos are optimum. Those that result in reduced survival are suboptimum.

Table 1 (continued)

Variable and source		Assumption
V_6	Boussu 1954 Elser 1968 Lewis 1969	Trout standing crops are correlated with the amount of usable cover present. Usable cover is associated with water ≥ 15 cm deep and velocities ≤ 15 cm/sec. These conditions are associated more with pool than riffle conditions. The best ratio of habitat conditions is about 50% pool to 50% riffle areas. Not all of a pool's area provides usable cover. Thus, it is assumed that optimal cover conditions for trout streams can be reached at < 50% of the total area.
V_7	Bjornn 1969 Phillips et al. 1975 Duff 1980	The average size of spawning gravel that is correlated with the best water exchange rates, proper redd construction, and highest fry survival is assumed to be optimum for average sized cutthroat trout. The percentage of total spawning area needed to support a good trout population was calculated from the following assumptions: 1. Excellent riverine trout habitat will support about 500 kg/hectare. 2. Spawners comprise about 80% of the weight of the population. 500 kg x 80% = 400 kg of spawners. 3. Cutthroat adults average about 0.2 kg each $\frac{400\ \text{kg}}{0.2\ \text{kg}}$ = 2,000 adult spawners 4. There are two adults per redd $\frac{2{,}000}{2}$ = 1,000 pairs 5. Each redd covers ≥ 0.5 m² 1,000 x 0.5 = 500 m² per hectare 6. There are 10,000 m² per hectare $\frac{500}{10{,}000}$ = 5% of total area

Table 1 (continued)

Variable and source		Assumption
V_8	Hartman 1965 Everest 1969 Bustard and Narver 1975a, b	The substrate size range selected for escape and winter cover by cutthroat fry and small juveniles is assumed to be optimum.
V_9	Pennak and Van Gerpen 1947 Hynes 1970 Binns and Eiserman 1979	The dominant substrate type containing the greatest numbers of aquatic insects is assumed to be optimum for insect production.
V_{10}	Needham 1940 Elser 1968 Hunt 1971 Horner and Bjornn 1976	The percent pools during late summer low flows that is associated with the greatest trout abundance is optimum.
V_{11}	Idyll 1942 Delisle and Eliason 1961 Chapman 1966 Hunt 1975	The average percent vegetation along the streambank is related to the amount of allochthanous materials deposited annually in the stream. Shrubs are the best source of allochthanous materials, followed by grasses and forbs, and then trees. The vegetational index is a reasonable approximation of optimal and suboptimal conditions for most trout stream habitats.
V_{12}	Anonymous 1979 Raleigh and Duff 1981	The average percent rooted vegetation and rocky ground cover that provides adequate erosion control to the stream is optimum.
V_{13}	Hartman and Gill 1968 Platts 1974 Sekulich 1974 Behnke and Zarn 1976 Binns 1977	The average annual maximal or minimal pH levels related to high survival of trout are optimum.
V_{14}	Binns 1979 Adapted from Duff and Cooper 1976	Flow variations affect the amount and quality of pools, instream cover, and water quality. Average annual base flows associated with the highest standing crops are optimum.

Table 1 (concluded)

	Variable and source	Assumption
V_{15}	Lewis 1969 Raleigh (in press)	Pool classes associated with the highest standing crops of trout are optimum.
V_{16}	Bjornn 1969 Cordone and Kelly 1961 Platts 1974 McCuddin 1977 Crouse et al. 1981	The percent fines associated with the highest standing crops of food organisms, embryos, and fry in each designated area is optimum.
V_{17}	Sabean 1976, 1977 Anonymous 1979	The percent of stream area shaded that is associated with optimal water temperatures and photosynthesis rates is optimum.

The above references include data from studies on related salmonid species. This information has been selectively used to supplement, verify, or complete data gaps on the habitat requirements of cutthroat trout.

Riverine Model

This model uses a life stage approach with five components: adult, juvenile, fry, embryo, and other.

Adult (C_A). C_A variables: V_4, V_5, V_{10}, and V_{15}

Case 1: where V_6 is $> (V_{10} \times V_{15})^{1/2}$

$$C_A = [V_4 \times V_6 \, (V_{10} \times V_{15})^{1/2}]^{1/3}$$

Case 2: where V_6 is $\leq (V_{10} \times V_{15})^{1/2}$

$$C_A = [V_4 \, (V_{10} \times V_{15})^{1/2}]^{1/2}$$

If V_4 or $(V_{10} \times V_{15})^{1/2}$ is ≤ 0.4 in either equation, then C_A = the lowest factor score.

Juvenile (C_J). C_J variables: V_6, V_{10}, and V_{15}

$$C_J = \frac{V_6 + V_{10} + V_{15}}{3}$$

or, if any variable is ≤ 0.4, then C_J = the lowest variable score.

Fry (C_F). C_F variables: V_8, V_{10}, and V_{16}

$$C_F = [V_{10} \, (V_8 \times V_{16})^{1/2}]^{1/2}$$

or, if V_{10} or $(V_8 \times V_{16})^{1/2}$ is ≤ 0.4, then C_F = the lowest factor score.

Embryo (C_E). C_E variables: V_2, V_3, V_5, V_7, and V_{16}

Steps:

A. A potential spawning site is an ≥ 0.5 m² area of gravel 0.3-8.0 cm in size covered by flowing water ≥ 15 cm deep. At each spawning site sampled, record:

1. The average water velocity over the site;
2. The average size of all gravel 0.3-8.0 cm;
3. The percentage of fines < 0.3 cm in the gravel; and
4. The total area in m² of each site.

B. Derive a spawning site suitability index (V_s) for each site by combining V_5, V_7, and V_{16} values for each site.

$$V_s = (V_5 \times V_7 \times V_{16})^{1/3}$$

C. Derive a weighted average ($\overline{V}_s$) for all sites included in the sample.

Select the best V_s scores until all sites are included, or until a total spawning area equal to, but not exceeding, 5% of the total cutthroat trout habitat has been included, whichever comes first.

$$\overline{V}_s = \frac{\sum_{i=1}^{n} A_i \, V_{si}}{\text{total habitat area}} \Big/ 0.05 \text{ (output cannot > 1.0)}$$

where: A_i = the area of each spawning site in m², but ΣA_i cannot exceed 5% of the total cutthroat habitat.

V_{si} = the individual SI scores from the best spawning areas until all spawning sites have been included or until SI's from an area equal to 5% of the total cutthroat habitat being evaluated has been included, whichever occurs first.

D. Derive C_E

C_E = the lowest score of V_2, V_3, or $\overline{V}_s$

Other (C_O). C_O variables: V_1, V_3, V_9, V_{11}, V_{12}, V_{13}, V_{14}, V_{16}, and V_{17}

$$C_O = \left[\frac{(V_9 \times V_{16})^{1/2} + V_{11}}{2} \times (V_1 \times V_3 \times V_{12} \times V_{13} \times V_{14} \times V_{17})^{1/N}\right]^{1/2}$$

where: N = the number of variables within the parentheses. Note that variables V_{12} and V_{17} are optional and, therefore, may be omitted (see page 18).

HSI determination. HSI scores may be derived for a single life stage, a combination of two or more life stages, or all life stages combined. In all cases, except for the embryo component (C_E), an HSI is obtained by combining one or more life stage component scores with the other component (C_O) score.

1. Equal Component Value Method. The equal component value method assumes that each component exerts equal influence in determining HSI. This method should be used to determine HSI unless information exists that individual components should be weighted differently. Components: C_A, C_J, C_F, C_E, and C_O

$$HSI = (C_A \times C_J \times C_F \times C_E \times C_O)^{1/N}$$

or, if any component is ≤ 0.4, then HSI = the lowest component value, or if C_A is < the equation value, then HSI = C_A.

where: N = the number of components in the equation.

Solve the equation for the number of components to be included in the evaluation. There will be a minimum of two, one or more life stage components and the component (C_O), unless only the embryo life stage (C_E) is being evaluated; then HSI = C_E.

2. Unequal Component Value Method. This method also uses a life stage approach with five components: adult (C_A), juvenile (C_J), fry (C_F), embryo (C_E), and other (C_O). However, the C_O component is divided into two subcomponents, food (C_{OF}) and water quality (C_{OQ}). It is assumed that the C_{OF} subcomponent can either increase or decrease the suitability of

the habitat by its effect on growth at each life stage except embryo. The C_{OQ} subcomponent is assumed to exert an influence equal to the combined influence of all other model components in determining habitat suitability. The method also assumes that water quality is excellent, $C_{OQ} = 1$. When C_{OQ} is < 1, HSI is decreased. In addition, when a basis for weighting exists, model component and subcomponent weights can be increased by multiplying each index value by multipliers > 1. Model weighting procedures must be documented.

Components and subcomponents: C_A, C_J, C_F, C_E, C_{OF}, and C_{OQ}

Steps:

A. Calculate the subcomponents (C_{OF} and C_{OQ}) of C_O

$$C_{OF} = \frac{(V_5 \times V_{16})^{1/2} + V_{11}}{2}$$

$$C_{OQ} = (V_1 \times V_3 \times V_{13} \times V_{14})^{1/4}$$

or, if any variable is ≤ 0.4, then C_{OQ} = the value of the lowest variable.

B. Calculate HSI by either the noncompensatory or the compensatory option.

Noncompensatory option. This option assumes that degraded water quality conditions cannot be compensated for by good physical habitat conditions. This assumption is most likely true for small streams (≤ 5 m wide) and for persistent degraded water quality conditions.

$$HSI = (C_A \times C_J \times C_F \times C_E \times C_{OF})^{1/N} \times C_{OQ}$$

or, if any component is ≤ 0.4, then HSI = the lowest component value × C_{OQ}.

where: N = the number of components and subcomponents inside the parentheses or, if the model components or subcomponents have unequal weights, then N = Σ of weights selected.

If only the embryo component is being evaluated, then $HSI = C_E \times C_{OQ}$.

Compensatory option. This method assumes that moderately degraded water quality conditions can be partially compensated for by good physical habitat conditions. This assumption is useful for large rivers (≥ 50 m wide) and for temporary, or short term, poor water quality conditions.

1) $HSI' = (C_A \times C_J \times C_F \times C_E \times C_{OF})^{1/N}$

or, if C_A is ≤ 0.4, then $HSI' = C_A$

where: N = the number of components and subcomponents in the equation, or if the model components or subcomponents have unequal weights, then N = Σ of weights selected.

2) If C_{OQ} is < HSI' , then $HSI = HSI' \times [1 - (HSI' - C_{OQ})]$; if not, HSI = HSI'.

3) If only the embryo component is being evaluated, follow the procedure in step 2, substituting C_E for HSI'.

Lacustrine Model

The following model is available to evaluate cutthroat trout lacustrine habitat. The lacustrine model consists of two components: water quality and reproduction.

Water Quality (C_{WQ}). C_{WQ} variables: V_1, V_3, and V_{13}

$$C_{WQ} = (V_1 \times V_3 \times V_{13})^{1/3}$$

or, if the SI scores for V_1 or V_3 are ≤ 0.4, then C_{WQ} = the lowest SI score for V_1 or V_3.

Note: Lacustrine cutthroat require a tributary stream for spawning and embryo development. If the embryo life stage habitat is to be included in the evaluation, use the embryo component steps and equations in the riverine model above, except that the area of spawning gravel needed is only about 1% of the total surface area of the lacustrine habitat.

Embryo (C_E). C_E variables: V_2, V_3, V_5, V_7, and V_{16}

$$\overline{V}_s = \frac{\sum_{i=1}^{n} A_i V_{si}}{\text{total habitat area}} /0.01 \text{ (output cannot > 1.0)}$$

HSI determination.

$$HSI = (C_{WQ} \times C_E)^{1/2}$$

If only the lacustrine habitat is evaluated, then HSI = C_{WQ}.

Interpreting Model Outputs

Model HSI scores for individual life stages, composite life stages, or for the species are a relative indicator of habitat suitability for the evaluation element. The HSI models, in their present form, are not intended to consistently predict standing crops of fishes throughout the United States. Standing crop limiting factors, such as interspecific competition, predation, disease, water nutrient levels, and length of growing season, are not included in the aquatic HSI models. The models contain physical habitat variables important in maintaining viable populations of cutthroat trout. If the model is correctly structured, a high HSI score for a habitat would indicate near optimal regional conditions for cutthroat trout for those factors included in the model, intermediate HSI scores would indicate average habitat conditions, and low HSI scores would indicate poor habitat conditions. An HSI of 0 does not always mean that the species is not present. An HSI of 0 means that the habitat is very poor and the species will be scarce or absent.

Cutthroat trout tend to occupy riverine habitats with very few other fish species present. They are usually competitively excluded by other trout species. Thus, factors of disease, interspecific competition, and predation usually will have little effect on the model. When the cutthroat trout model is applied to cutthroat trout streams with similar water quality and length of growing season, it should be possible to calibrate the model output to reflect size of standing crops within some reasonable confidence limits. This possibility, however, has not been tested with the present model.

Sample data sets selected by the authors to represent high, intermediate, and low habitat suitabilities are given in Table 2, along with the SI's and HSI's generated by the cutthroat trout riverine model. The model outputs calculated from the sample data sets (Tables 3 and 4) reflect what the authors believe carrying capacity trends would be in riverine habitats with the listed characteristics; thus, the model meets the specified acceptance level.

Habitat survey form used for the South Fork of Coeur D'Alene River and tributaries.

STREAM: ____________________ REACH: ____________________ DATE: ________________ PAGE _ OF _

FLOW CONDITIONS: __________ WEATHER: ________________ CREW: ________________

Habitat Unit Data			Surface Area/vol			Streambed Characteristics					Streambank Characteristics						Other Characteristics			Photo	Comments
											LEFT			RIGHT							
Unit #	Unit Type	struct asso	L	W	Max D	Pri Sub	Sec Sub	Emb	AV Abun	AV Type	Stabi-lity	Bank Veg	Veg W	Stabi-lity	Bank Veg	Veg W	Cover	Woody debris	Ch. Alt		

Codes used for habitat survey of Coeur d'Alene River and tributaries.

Habitat Code:

G = Glide = 1
P = Pool
R = Riffle
S = Secondary Channel
D = Dry

Pool Type & Code:

3 = Backwater
4 = Trench
5 = Plunge
6 = Lateral Scour
7 = Damned

Riffle Type & Code:

9 = Low gradient - bedrock
10 = Low gradient - gravel
11 = Low gradient - cobble
12 = Low gradient - boulder
13 = Rapids
14 = Cascades

Structural Association Code:

B = Boulder
C = Culvert
D = Beaver Dam
E = Enhancement Structure
F = Falls
O = Others
P = Pocket Water (riffles)
R = Bar
S = Stream Bend
T = Rootwad
W = Large Wood

Substrate Codes:

B = Boulder (>256mm)
LC = Large Cobble (128-256mm)
SC = Small Cobble (64-128mm)
LG = Large Gravel (16-64mm)
SG = Small Gravel (2-16mm)
Sd = Sand (0.062-2mm)
St/C = Silt/Clay (<0.062mm)

Codes for Embeddedness, Stability, Bank Veg, Veg Width, Cover, Channel Alteration:
(From, Montana Habitat Assessment Protocols)

O = Optimum
SO = Sub-optimum
M = Marginal
P = Poor

Codes for Aquatic Vegetation (AV) Abundance & Woody Debris:

H = High
M = Moderate
L = Low

A = Algae
M = Macrophyte

Stream ______________________ Site ______________________

Date ______________________ Investigator ______________________

Habitat Parameter	Category			
	Optimal	Sub-Optimal	Marginal	Poor
Embeddedness Score (______)	Gravel, cobble or boulder particles are between 0-25% surrounded by fine sediment (particles less than 6.35mm (.25")) 16-20	Gravel, cobble or boulder particles are between 25-50% surrounded by fine sediment. 11-15	Gravel, cobble or boulder particles are between 50-75% surrounded by fine sediment. 6-10	Gravel, cobble, and boulder particles are over 75% surrounded by fine sediment. 0-5
Channel Alteration (channelization, straightening, dredging, other alterations) Score (______)	Channel alterations absent or minimal: stream pattern apparently in natural state. 16-20	Some channelization present, usually in areas of crossings, etc. evidence of past alterations (before past 20 yr) may be present, but more recent channel alteration is not present. 11-15	New embankments present on both banks; and 40 to 80% of the stream reach channelized and disrupted. 6-10	Banks shored with gabion or cement; over 80% of the stream reach channelized and disrupted. 0-5
Bank Stability (Score each bank) Note: determine left or right side while facing downstream Score (______) (left) Score (______) (right)	Banks stable; no evidence of erosion or bank failure; little apparent potential for future problems. 9-10	Moderately stable; infrequent, small areas of erosion mostly healed over. 6-8	Moderately unstable; moderate frequency and size of erosional areas; up to 60% of banks in reach have erosion; high erosion potential during high flow. 3-6	Unstable; many eroded areas; "raw" areas frequent along straight section and bends; obvious bank sloughing; 60-100% of banks have erosion cars on side slopes. 0-2
Bank Vegetation Protection (note: reduce scores for annual crops and weeds which do not hold soil well, eg knapweed) Score (______)	Over 90% of the streambank surfaces covered by stabilizing vegetation; vegetative disruption minimal or not evident; almost all plants allowed to grow naturally. 9-10	70-90% of the streambank surfaces covered by vegetation; disruption evident, but not affecting full plant growth potential to any great extent; more than one-half of the potential plant height evident. 6-8	50-70% of the streambank surfaces covered in vegetation; disruption obvious; patches of bare soil or closely cropped vegetation common; less than one-half of potential plants height remaining. 3-5	Less than 50% of the streambank surfaces covered by vegetation; extensive disruption of vegetation; vegetation removed to 2 inches or less. 0-2
Vegetated Zone Width (score zone for each side of stream) Score (______)	Width of vegetated zone > 100 feet. 9-10	Width of vegetated zone 30-100 feet. 6-8	Width of vegetated zone 10-30 feet. 3-5	Width of vegetated zone <10 feet. 0-2

[1]Adapted from the Montana Habitat Assessment Field Data Sheet.

Stream ______________________ Site ______________________

Date ______________________ Investigator ______________________

Habitat Parameter	Category			
	Optimal	Sub-Optimal	Marginal	Poor
Bottom Substrate/ Available Cover	Greater than 50% mix of snags, submerged logs, undercut banks, rubble or other stable habitat and at stage to allow full colonization potential (i.e., logs/snags that are not new fall and not transient).	30-50% mix of stable habitat; well-suited for full colonization potential; adequate habitat for maintenance of populations; presence of additional substrate in the form of newfall, but not yet prepared for colonization (may rate at high end of scale).	10-50% mix of stable habitat; habitat availability less than desirable; substrate frequently disturbed or removed.	Less than 10% stable habitat; lack of habitat is obvious; substrate unstable or lacking.
Score (______)	16-20	11-15	6-10	0-5

[1]Adapted from the Montana Habitat Assessment Field Data Sheet.

Indicators of Hydrologic Alteration

User's Manual

The Nature Conservancy

with
Smythe Scientific Software

July 2001

Day-2 Handout 1

Indicators of Hydrologic Alteration

User's Manual

The Nature Conservancy

with

Smythe Scientific Software

July 2001

Table 1

Summary of 33 hydrologic parameters used in the Indicators of Hydrologic Alteration software, and their characteristics.

IHA Statistics Group	*Hydrologic Parameters*	*Ecosystem Influences*
Magnitude of monthly water conditions	Mean value for each calendar month	• Habitat availability for aquatic organisms • Soil moisture availability for plants • Availability of water for terrestrial animals • Availability of food/cover for fur-bearing mammals • Reliability of water supplies for terrestrial animals • Access by predators to nesting sites • Influences water temperature, oxygen levels, photosynthesis in water column
	Subtotal 12 parameters	
Magnitude and duration of annual extreme water conditions	Annual 1-day minima	• Balance of competitive, ruderal, and stress- tolerant organisms
	Annual minima, 3-day means	• Creation of sites for plant colonization
	Annual minima, 7-day means	• Structuring of aquatic ecosystems by abiotic vs. biotic factors
	Annual minima, 30-day means	• Structuring of river channel morphology and physical habitat conditions
	Annual minima, 90-day means	• Soil moisture stress in plants
	Annual 1-day maxima	• Dehydration in animals
	Annual maxima, 3-day means	• Anaerobic stress in plants
	Annual maxima, 7-day means	• Volume of nutrient exchanges between rivers and floodplains
	Annual maxima, 30-day means	• Duration of stressful conditions such as low oxygen and concentrated chemicals in aquatic environments
	Annual maxima, 90-day means	• Distribution of plant communities in lakes, ponds, floodplains
	Number of zero-flow days (zero flow)	• Duration of high flows for waste disposal, aeration of spawning beds in channel sediments
	7-day minimum flow/mean for year (base flow)	
	Subtotal 12 parameters	

Table 1, continued

IHA Statistics Group	*Hydrologic Parameters*	*Ecosystem Influences*
Timing of annual extreme water conditions	Julian date of each annual 1-day maximum	• Compatibility with life cycles of organisms • Predictability/avoidability of stress for organisms
	Julian date of each annual 1-day minimum	• Access to special habitats during reproduction or to avoid predation • Spawning cues for migratory fish Evolution of life history strategies, behavioral mechanisms
	Subtotal 2 parameters	
Frequency and duration of high and low pulses Pulse is defined based on 25th percentile and 75th "	Number of low pulses within each year	• Frequency and magnitude of soil moisture stress for plants • Frequency and duration of anaerobic stress for plants
	Mean duration of low pulses within each year	• Availability of floodplain habitats for aquatic organisms • Nutrient and organic matter exchanges between river and floodplain
	Number of high pulses within each year	• Soil mineral availability • Access for waterbirds to feeding, resting, reproduction sites
	Mean duration of high pulses within each year	• Influences bedload transport, channel sediment textures, and duration of substrate disturbance (high pulses)
	Subtotal 4 parameters	
Rate and frequency of water condition changes	Means of all positive differences between consecutive daily values	• Drought stress on plants (falling levels)
	Means of all ~~positive~~ negative differences between consecutive daily values Number of hydrological reversals	• Entrapment of organisms on islands, floodplains (rising levels) • Desiccation stress on low-mobility streamedge (varial zone) organisms
	Subtotal 3 parameters	
	Grand total 33 parameters	

Comparison of One and Two-dimensional Open Channel Flow Models for a Small Habitat Stream

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ABSTRACT: Recent developments in physical habitat calculations have introduced the use of two and three-dimensional hydrodynamic model components. Practitioners are unfamiliar with the more detailed hydrodynamic models and their applicability to smaller streams characterized by small flow depths and rapid bathymetric variations. Our objective was to evaluate and compare the results of a two-dimensional model depth and velocity simulation with conditions simulated using the one-dimensional hydraulic models using typical field data collected for instream flow studies. One-dimensional (transect) profile and velocity data were collected at two discharges and two-dimensional bathymetric data were collected separately. The Physical Habitat Simulation system (PHABSIM) hydraulic models were calibrated to the higher discharge velocity and water surface measurements and then used to predict the low discharge values. Then the CDG2D finite element model, including automatic super-critical/sub-critical evaluation and a continuous wet/dry area solution procedure, was used to simulate both discharges with minimal calibration. Comparisons of velocity and water surface elevation predictions for full and split flow portions of the channel were performed. These comparisons show that for the available data and simulated flow conditions the two methods offer comparable precision of prediction, but that the two-dimensional model captures complex flow situations where significant transverse flow is present. Implications for habitat modeling and observations on data collection procedures for both categories of models are discussed.

KEY WORDS: Calibration, depth, hydraulics, Physical Habitat Simulation system, PHABSIM, two-dimensional model, velocity, verification.

INTRODUCTION

One-dimensional hydraulic models have been used in habitat studies since the late 1970s. The Physical Habitat Simulation system (PHABSIM) (Milhous et al. 1989) developed at the Midcontinent Ecological Science Center (MESC) contains many empiricisms to handle such things as simulating changing edge conditions, simulating water depths greater than the highest measured points, and other practical problems. An important empiricism employed in the one-dimensional model application in this study is use of a measured velocity distribution as a template for simulation of velocities at unmeasured discharges. Implicit in the one-dimensional approach is application of a representative cross section to a channel length determined by the smaller of hydraulic breakpoints or changes in important habitat phenomena. The field data required for this approach include cross-sectional measurements of velocity and depth for a number (MESC recommends three or more) of selected discharges at the site.

The empirical approach can lead to errors in prediction of depth and velocity, especially when channel conditions approach the bounding assumptions of the empirical models. Two-dimensional models hold the promise of providing a spatially explicit solution of the flow field (Bechera et al. 1994; Ghanem et al.1994; U.S. Army Corps of Engineers 1996). By attempting to model more of the detailed physics (hydrodynamics) of the streamflow including such things as eddies, split channels and secondary channels associated with islands and flow reversals, the potential exists for a more accurate description of habitat events (Mathews and Bao 1991; Leclerc et al. 1995; Tarbet and Hardy 1996).

Instream flow practitioners in provincial and federal agencies in Canada and the United States are becoming increasingly aware of the potential for use of two-dimensional hydraulics in instream flow studies. Both skepticism and hope are expressed for better representation of instream habitat conditions. Unfortunately, there are but a few studies verifying two-dimensional results for low flow or small-scale situations and none we know of have used field data collected for an instream habitat study to compare the results of using one-dimensional and two-dimensional hydraulic models. This study was designed to address two areas of interest to instream flow decision makers: (1) the use of typical field data from a hydraulically interesting environment to compare one-dimensional and two-dimensional hydraulic model performance, and (2) the identity of strengths and weaknesses of data collection techniques to develop data collection guidelines. This study is part of a larger project to evaluate the impact of two-dimensional modeling on the overall habitat evaluation process, including a variety of sites and integration of biological parameters.

The site selected for this study was on the Elbow River in Calgary, Alberta, Canada, where a standard instream habitat study using PHABSIM was in progress. Distributed bathymetric and substrate data for the two-dimensional model were also collected at the same site assuming that the channel had not changed. Two sets of cross-sectional (water surface elevation and velocity) data were available; one for a higher discharge (approximately 21 m^3/s), and one for a lower discharge (approximately 4 m^3/s). Although MESC recommends that instream flow studies be conducted with as many discharge data sets as possible, to allow a blind test, the one-dimensional model was calibrated with the higher discharge and then used to predict depth and velocity at the cross sections for the lower discharge. The two-dimensional model was run with minimal calibration for both discharges. For both models, the results were compared to the field measurements and are reported herein.

SITE DESCRIPTION

The Elbow River arises in the Canadian Rockies near the continental divide and flows north-east through Calgary, Alberta, where it joins the Bow River. The selected study site lies about 1 km downstream of the Glenmore Reservoir, which is the primary source of drinking water for the City of Calgary and about 4 km upstream of the confluence with the Bow River. The mean annual flow of the Elbow is about 8.5 m^3/s (Kellerhalls et al. 1972). The channel is 35 to 50- m wide and the mean slope is roughly 0.0037. At the study

site the channel bed consists of a cobble and boulder alluvium with areas of exposed sandstone bedrock and a few colluvial sandstone boulders. A few areas of gravel are found within the study area, but the dam upstream has cut off the sediment supply. An island splits the flow along about one-third of the 315-m study site and a moderate bend is entered at the downstream end of the site. The south bank abuts the valley wall, which is steep, high, and forested. The bank north of the island has been subject to significant erosion over the last two years and property owners have undertaken some protection works, including riprap and log walls along parts of the bank. The study area contains pools for holding and resting, velocity refugia behind colluvial boulders, and nearby gravel areas for spawning; ideal habitat conditions for brown trout *(Salmo Trutta)*.

The study site was selected to provide a challenging test for both one-dimensional and two-dimensional models. The site has fairly steep segments and the flow division around the island is somewhat complex with significant lateral shifts in the flow. There are also a number of large rocks and boulders in the stream. At the same time, the site was easily accessible and is entirely wadeable at low flow.

DATA COLLECTION

The data collection consisted of two sets of cross-sectional topographic and velocity data for the one- dimensional PHABSIM approach and one set of topographic measurements for the two-dimensional approach. Figure 1 shows a plan view of the test site indicating the location of the PHABSIM cross sections (indicated as T1 – T8) and of the distributed topographic points (indicated as small circles). Details of the data collection procedures are considered in the following sections.

One-dimensional Model Transect Data

The one-dimensional model data was collected as part of an ongoing PHABSIM study. It consisted of depth and velocity measurements taken along 8 transects at a high discharge of approximately 21 m^3/s and a low discharge of 4 m^3/s. The high discharge data were collected on 15 June and the low flow measurements were made on 25 October 1995. An extreme high flow event occurred during late May and early June 1995, causing significant alterations to the channel, invalidating earlier measurements, and leaving some uncertainty as to channel stability. Four depth and velocity data sets would have allowed use of three observations in calibration of the one-dimensional models as recommended by the MESC and the fourth in a blind comparison. However, one purpose of this paper was to use typical study data to provide a real world example of model performance; therefore, available data were used.

Data collection in any river is subject to several potential sources of error. Among the most common are unsteady flow, channel change between measurements, and measure-

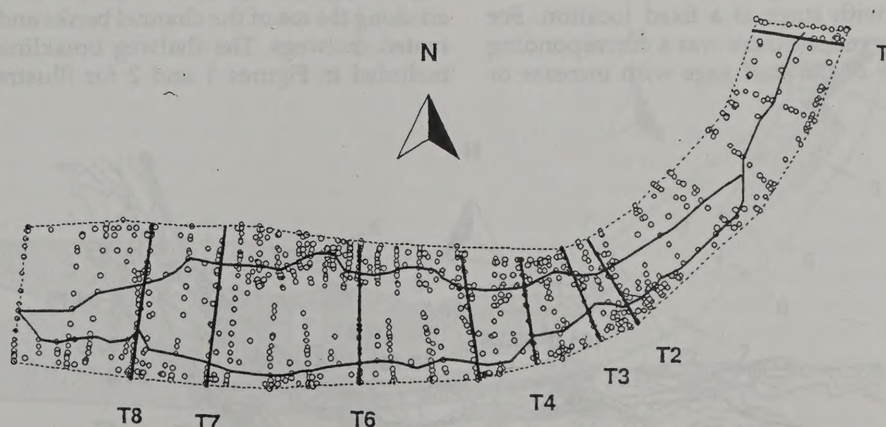

FIGURE 1. *Site plan view and data collection locations on the Elbow River.*

ment error. During collection of the two one-dimensional data sets, careful use of a staff gage indicated that changes in discharge occurred. Discharge values calculated from individual transects varied as much as 25% at the high discharge and 50% at the low discharge. A multiple flow calibration of the one-dimensional backwater model (called WSP) was performed to accommodate the unsteady flow.

Measurement of the bed topography along the transects used in the one-dimensional model was accomplished using standard surveying equipment above the water surface and using depth measured from a wading rod for wet areas. Because high discharge was greater than had been anticipated, additional error may have been introduced when transect endpoints were moved. These two circumstances resulted in vertical differences of up to 0.1 m and horizontal differences of up to 2 m encountered in the bed profile between the two measured discharges. The bed profile derived from the low discharge measurements was chosen as most representative of the conditions in the Elbow River at the time the two-dimensional data were collected.

These kinds of data collection problems are typical of field measurement in rivers. Because a staff gage had been placed and read at the beginning and end of measurements at each transect, we were able to correlate the changes in discharge observed at individual transects with stage at a fixed location. For most observations there was a corresponding rise or fall of the staff gage with increase or decrease of the discharge measured at the transects. Those transects with an obvious deviation from this correlation were given less weight in the calibration process.

Distributed Topography and Substrate Data

The distributed topographic data were obtained using a total station on 29 and 30 August 1995. A total of 1,126 points were measured with an overall average spacing of about 6 m. As is shown in Figure 1, the density varied considerably with a generally finer resolution between sections 3 and 8 and a very fine resolution through the channel on the north side of the island. The general pattern used by the surveyors tended to be cross sectional with some intermediary points to delineate channel features and two very large colluvial boulders. In the two-dimensional model, definition of bed topography is achieved by creating a triangulated irregular network (TIN) from the field topography data. The data collection pattern caused some problems in the triangulation as situations arose where a triangle on the side of the channel had two vertices on the top of the bank and one near the center of the channel. Linear interpolation from the TIN then results in an artificial wedge shaped "side-channel bar" projecting into the channel. To alleviate this effect, longitudinal "breaklines" were threaded along the toe of the channel banks and estimated thalwegs. The thalweg breaklines are included in Figures 1 and 2 for illustration.

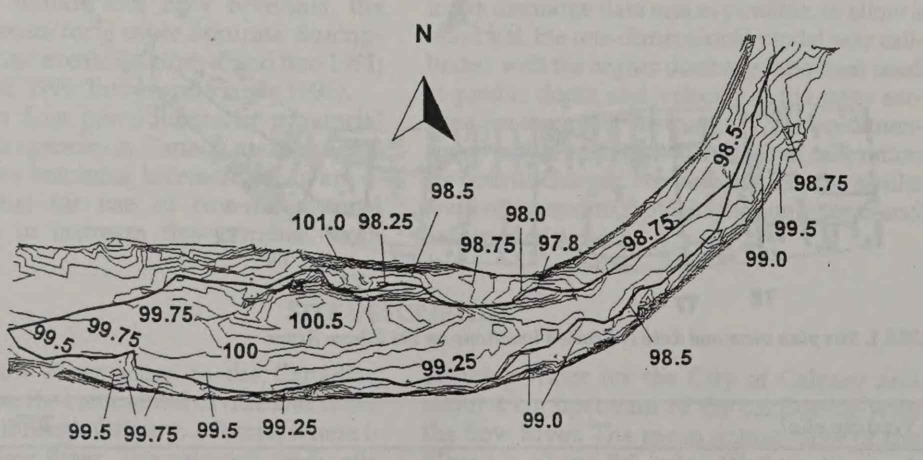

FIGURE 2. *Elbow River bed topography from the two-dimensional survey.*

These breaklines were used to interpolate additional points at triangle edge intersections. Thus, the direction of the interpolation is corrected while using the same triangulation procedure. Figure 2 shows the bed elevation contour map derived from the distributed data including the breaklines.

At the same time as the topographic survey, a substrate mapping exercise was carried out. Areas of relatively homogeneous substrate were identified by visual observation both at stream level (while wading) and from the vantage of the high south-eastern bank. These areas were delineated and surveyed as polygons using the total station. Figure 3 shows a map of these polygons and Table 1 indicates a description of the substrate type, a value of PHABSIM substrate code, and an assumed value of hydrodynamic roughness height for use in the two-dimensional model. The roughness values were then transferred to the bed topographic points. In a habitat study, the substrate codes would be filtered through a suitability function such as those used in the habitat models within PHABSIM.

TABLE 1
Elbow River substrate and bed roughness height used in Figure 3.

Map Key	Substrate Code	Description	Roughness Height (m)
1	4.0	sand	0.03
2	5.3	gravel	0.05
3	5.7	cobble	0.07
4	6.5	large cobble	0.2
5	6.9	small boulder	0.3
6	7.2	large boulder	0.5
7	7.6	very large boulder or trees	1.5

ANALYSIS AND MODEL CALIBRATION TO THE HIGH FLOW

PHABSIM

Given adequate topographical and water surface profile observations, the recommended procedure for hydraulic simulation in PHABSIM is to use a step-backwater model to describe the water surfaces and the IFG4 program to distribute velocities across the channel. The IFG4 program has options for using point discharges measured at a calibration flow to calculate a set of point values of Manning's n across each transect. These "velocity distribution" n values are then used as a template to distribute velocity across the channel at simulated discharges. Using water surface elevation values for each transect for each discharge derived from the WSP backwater model, the IFG4 program proportionately dis-

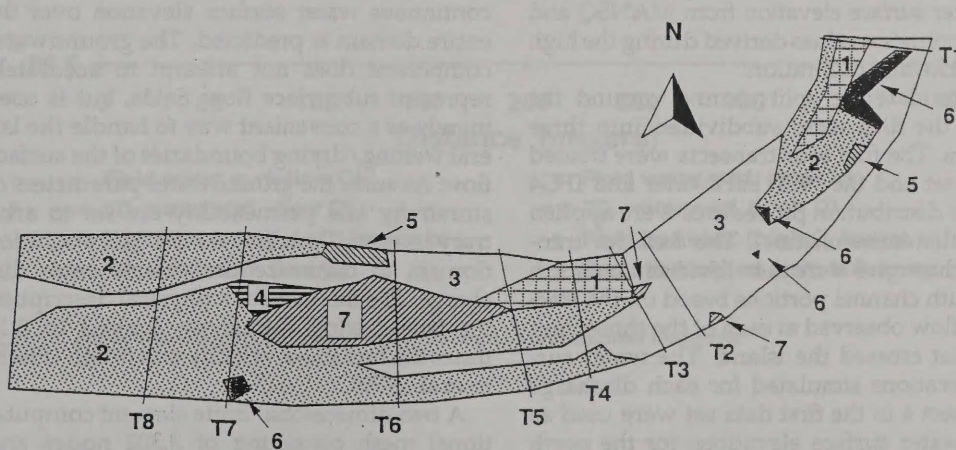

FIGURE 3. *Map of the Elbow River substrate and bed roughness.*

tributes velocities while maintaining continuity through each transect. When several calibration data sets are available, velocity templates for different ranges of flow can be prepared to limit the range of extrapolation from observed conditions. Because we were limited to two data sets, the one-dimensional hydraulic models were calibrated to the high discharge data with no knowledge of the low discharge observations. This allowed a blind comparison of water surface elevation and velocity prediction when the low discharge was simulated. Use of one discharge for calibration of these empirical models places a heavy burden on the assumptions and empiricisms built into the PHABSIM, and in that sense, is a demanding test of these models.

Initial water surface elevations for the WSP backwater model can be generated using the PHABSIM program, MANSQ. This program uses a power function of the ratio of simulated discharge to observed discharge to adjust conveyance at different discharges at each transect. When more than one discharge measurement is available for calibration, the exponent is adjusted until good agreement of simulated versus observed water surface elevations is achieved for all discharges. Lacking multiple discharge measurements, an empirically derived median value of 0.22 can be used for this exponent in gravel- and cobble bed rivers (Milhous 1987). The water surface profile for the low discharge was calculated in the WSP model using the initial water surface elevation from MANSQ and the Manning's n values derived during the high flow backwater calibration.

To simulate the split channel around the island, the data were subdivided into three portions. The first four transects were treated as one set and the WSP backwater and IFG4 velocity distribution procedures were applied across the entire channel. The data for transects 4 through 8 were then divided into north and south channel portions based on the fraction of flow observed at each of the three transects that crossed the island. The water surface elevations simulated for each discharge at transect 4 in the first data set were used as initial water surface elevations for the north and south channel backwater simulations. The same backwater procedures were then followed for the two split channels as for the combined channel. Manning's n values were adjusted for both channels to obtain minimal error in water surface elevation along each side channel as well as for the north and south portions of transect 8 while avoiding an unrealistic range or oscillation of n values between transects. That is, some error in fitting the high flow backwater profile was tolerated to avoid unrealistic variation in Manning's n between transects.

Due to the unsteady flow conditions during measurement, the backwater model was calibrated to three discharges: 21.7, 20.7 and 20.3 m^3/s. Staff gage and calculated discharge values for each transect were used to determine which of the three simulated backwaters would be applied to each transect. The profiles shown on Figure 4a and 4b illustrate the accuracy with which the water surface profile was simulated at the calibration discharges using the one-dimensional model. The mean absolute calibration error among the eight transects was 0.011 m.

Two-dimensional Model

The two-dimensional (depth-averaged) computational model is the CDG-2D model developed at the University of Alberta (Ghanem et al. 1994, 1995, 1996). This model uses a Petrov-Galerkin upwinding scheme for stability and jump capturing. It can therefore predict, without intervention, regions of supercritcal flow and associated transitions. The model also incorporates a highly simplified groundwater flow model for flow in dry (water surface below ground surface) areas. A continuous water surface elevation over the entire domain is predicted. The groundwater component does not attempt to accurately represent subsurface flow fields, but is used merely as a convenient way to handle the lateral wetting/drying boundaries of the surface flow. As such, the groundwater parameters of storativity and permeability are set to arbitrary but small values over the entire solution domain to minimize the groundwater discharge. The model uses a physical description for lateral eddy diffusivity, limited to 0.14 times the bed shear velocity and depth (Fischer et al. 1979).

A two-dimensional finite element computational mesh consisting of 3,302 nodes and 6,508 linear triangular elements was generated. The mesh was created in an unstructured fashion and the primary criteria for refinement was topographic matching. This was assessed visually by overlain contour maps in the mesh generation program. At each node the bed elevation and roughness height were

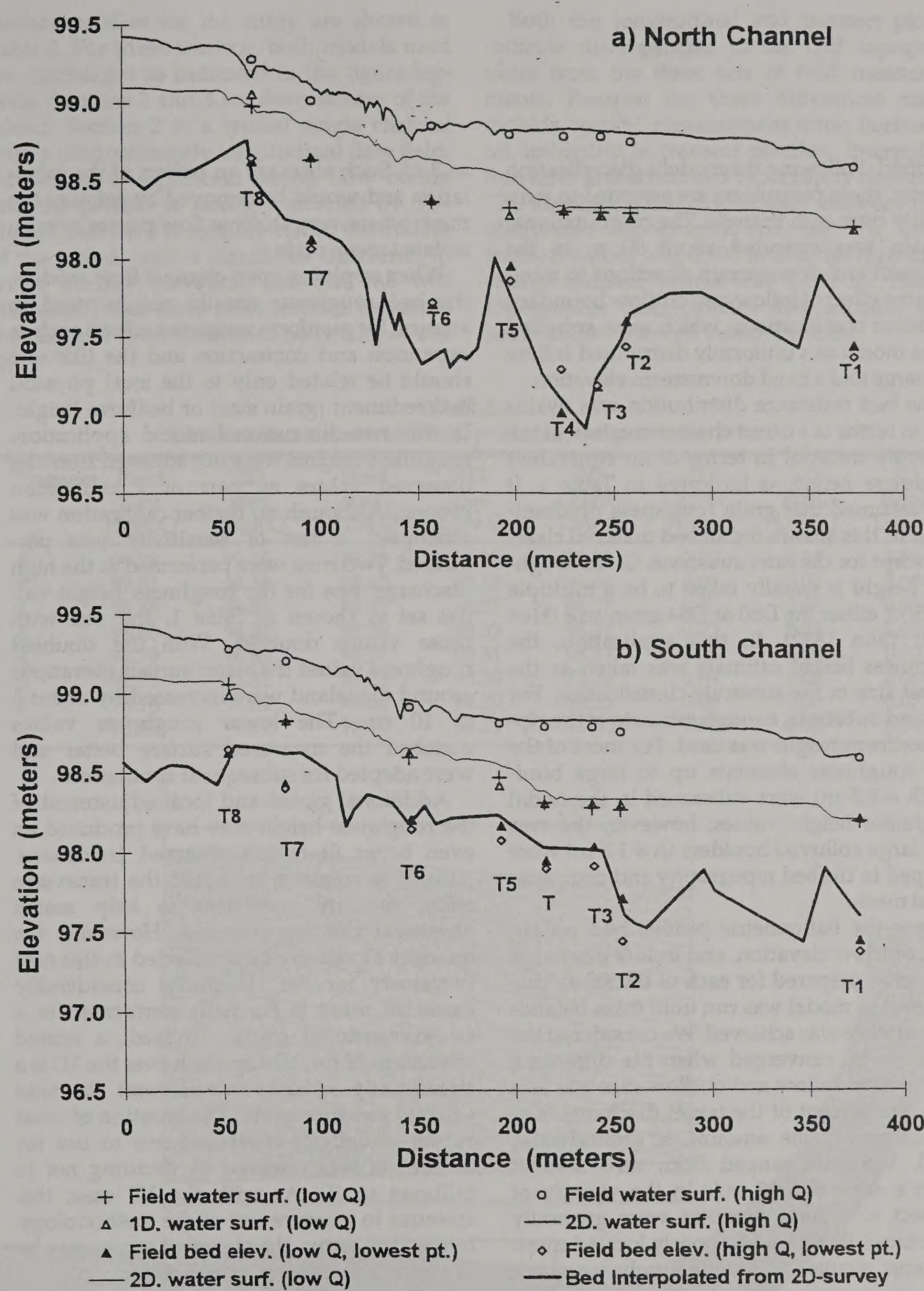

FIGURE 4. *Elbow River longitudinal profiles for north and south channel thalwegs.*

specified. Following the model's discretization scheme, these parameters are assumed to vary linearly over each triangle. The computational domain was extended about 50 m in the upstream and downstream directions to minimize the effect of inflow and outflow boundary condition specifications, which were supplied to the model as a uniformly distributed inflow discharge and a fixed downstream elevation.

The bed resistance distribution was evaluated in terms of a direct characterization of the substrate material in terms of an equivalent roughness height as indicated in Table 1. It was assumed that grain roughness predominated in this stream for all bed material classes, except for the sand substrate. Grain roughness height is usually taken to be a multiple (1 – 5) of either the D50 or D84 grain size (Hey 1979; Yalin 1992). In this application, the roughness height estimate was taken as the largest size in the substrate classification. For the sand substrate, a rough estimate of the ripple bedform height was used. For most of the bed, roughness elements up to large boulder (h = 0.5 m) were subsumed in the nodal roughness height values; however, the two very large colluvial boulders (h = 1.5 m) were mapped in the bed topography and computational mesh.

Once the bathymetric profile, bed roughness, outflow elevation, and inflow discharge data were prepared for each of the study discharges the model was run until mass balance convergence was achieved. We considered the model to be converged when the difference between the inflow and outflow rate was less than one percent of the target discharge (i.e., approximately the amount of groundwater flow). Velocities ranged from zero m/s at water's edge to 2.55 m/s in the vicinity of transect 6. Froude numbers were generally subcritical, though a few poorly located mesh elements resulted in Froude numbers as high as 3.65. Such areas are an artifact of the calculation and would be removed by refining the mesh where very shallow flow passes over an isolated mesh node.

When applying open-channel flow models, the bed roughness should not be used to account for planform resistance effects such as expansion and contraction and the like and should be related only to the local physical bed sediment (grain size) or bedform height. In this two-dimensional model application, roughness heights were not adjusted from the observed values as part of a calibration process. Although no further calibration was attempted, a test of sensitivity was performed. Two runs were performed at the high discharge: one for the roughness height values set as shown in Table 1, and one with those values doubled. With the doubled roughness values the water surface elevations around the island were increased by about 5 to 10 cm. The lower roughness values matched the measured surface better and were adopted for subsequent simulations.

Additional global and local adjustment of the roughness height may have produced an even better fit to the observed conditions. Also, it is common to adjust the transverse eddy viscosity coefficient to help match observed velocity patterns. However, the quantity of velocity data collected in this case (necessary for the 1D study) considerably exceeded what is normally performed in a two-dimensional study. Indeed, a touted advantage of the 2D approach over the 1D is a significantly reduced requirement for field velocity measurements. The question of what subset of velocity measurements to use for calibration was resolved by deciding not to calibrate at all. As with the 1D case, this amounts to a severe test of the methodology. In practical terms, the observed errors may be useful in indicating an upper bound.

COMPARISONS

The results of the two models and the measurements for the high and low discharges are compared in Figures 5-8. Figures 4a and 4b show longitudinal profiles of bed and water surface along the north and south thalwegs. For the predicted two-dimensional values on these profiles, a single discharge (low = 3.7 m^3/s, high = 23.2 m^3/s) was used whereas the one-dimensional results were calculated for separate (i.e., locally measured) discharges at each transect. Figures 6a, 7a, and 8a show cross-sectional elevations at sections 2, 4 and 6. Figures 6b, 7b, and 8b show corresponding high discharge velocity profiles. Figures 6c, 7c, and 8c show velocity profiles for the low discharge. The observed and simulated water

surface profiles for the study are shown in Table 2. For these sections, both models used the discharges as indicated in the figure legends. Sections 2 and 4 are downstream of the island. Section 2 is a typical single channel with a predominantly longitudinal flow field. At section 4, significant lateral flow occurs and the pattern is strongly affected by discharge. Section 6 is roughly across the middle of the island, with a significant difference in water surface elevation between the two channels. These three cross sections represent the range of flow conditions occurring at this site.

Both the longitudinal and transect plots indicate discrepancies in the bed topographies from the three sets of field measurements. Reasons for these differences may include vertical measurement error, horizontal ambiguity in transect position, interpolation error and actual bed topography changes. The absolute mean discrepancy between the distributed topography and the low flow transect values was 0.193 m and the high discharge transect values was 0.180 m. These topographic discrepancies may account for some of the observed velocity errors.

TABLE 2

Water surface elevations: Field, predicted, and prediction error.

Transect	Field Elev. High Q	2D Elev. High Q	Field Elev. Low Q	1D Elev. Low Q	2D Elev. Low Q	2D Error High Q	1D Error Low Q	2D Error Low Q
8	99.28	99.16	99.05	98.98	98.91	-0.12	-0.08	-0.14
7	99.01	99.10	98.65	98.63	98.65	0.09	-0.02	0.00
6	98.85	98.85	98.37	98.37	98.37	0.00	-0.01	0.00
5	98.80	98.83	98.28	98.33	98.33	0.03	0.05	0.05
4	98.79	98.83	98.31	98.31	98.33	0.05	0.00	0.02
3	98.79	98.82	98.28	98.30	98.34	0.04	0.02	0.06
2	98.76	98.82	98.26	98.30	98.33	0.06	0.03	0.07
1	98.59	98.61	98.19	98.21	98.20	0.02	0.02	0.01

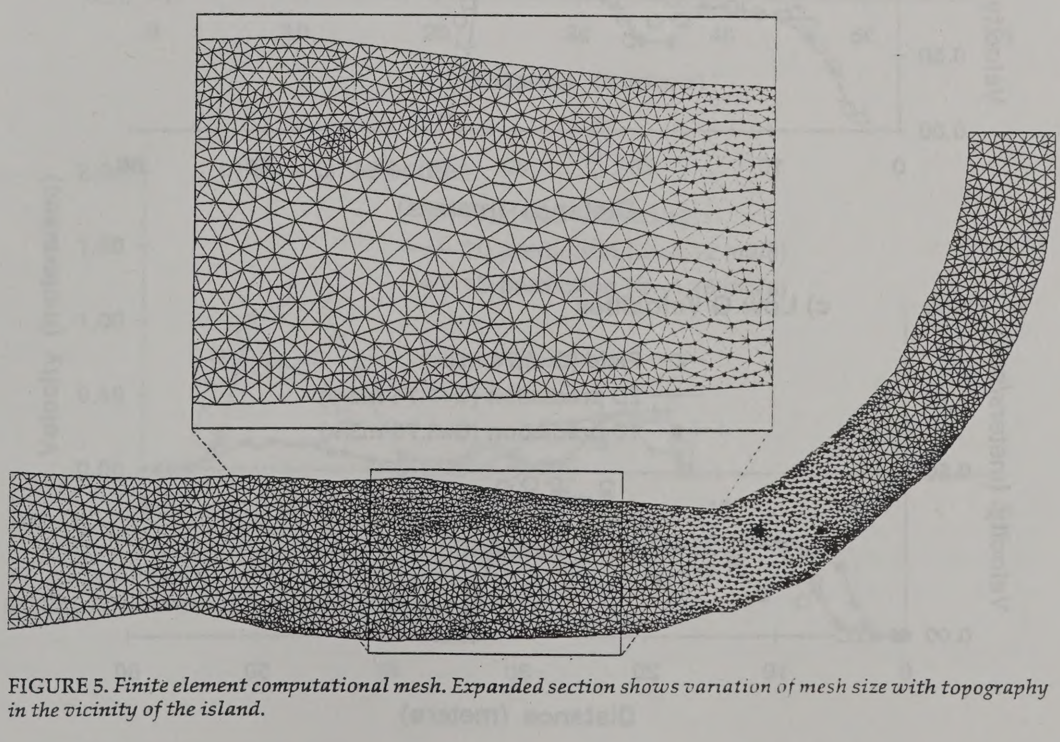

FIGURE 5. ***Finite element computational mesh. Expanded section shows variation of mesh size with topography in the vicinity of the island.***

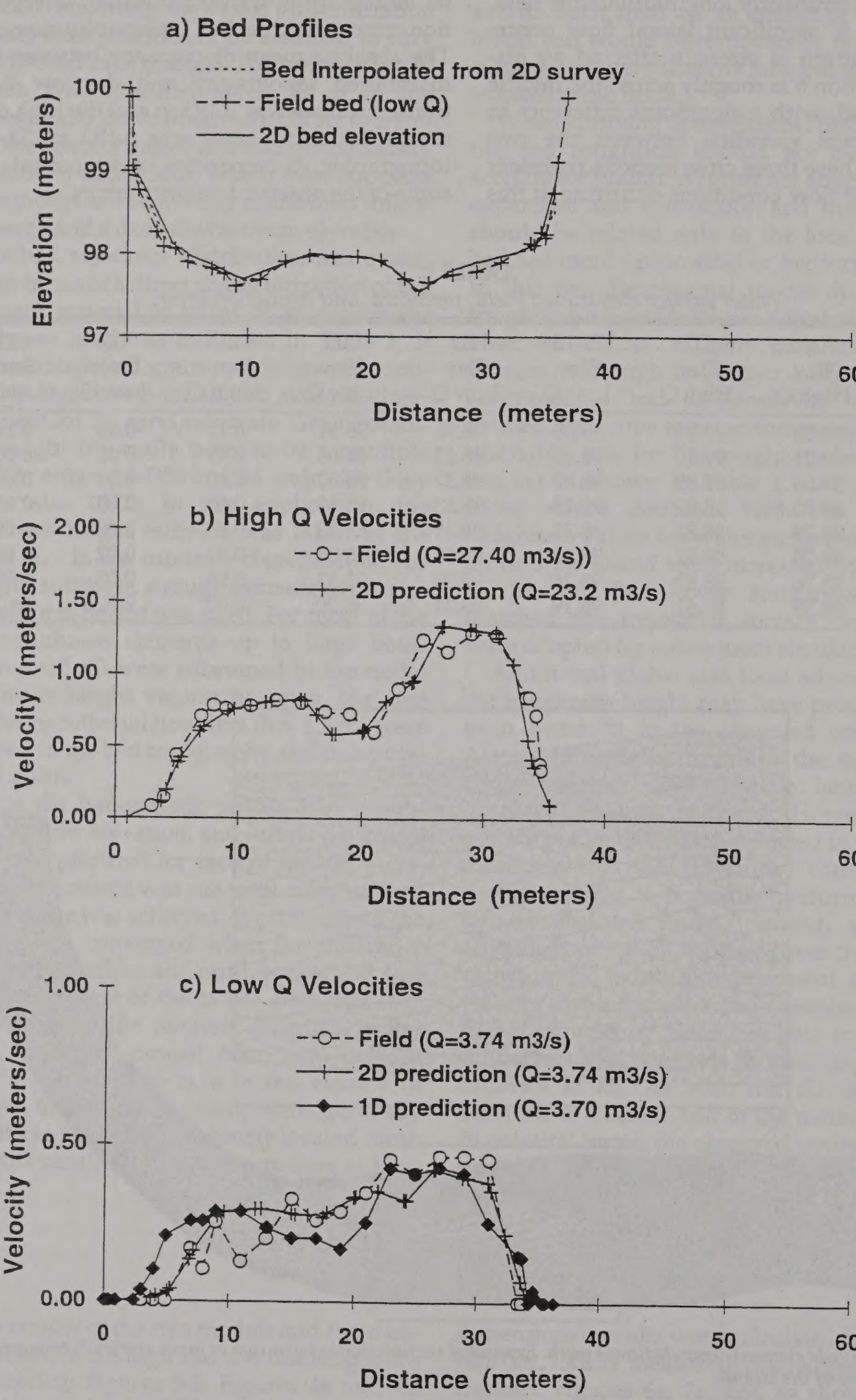

FIGURE 6. *Bed and velocity profiles for Transect 2.*

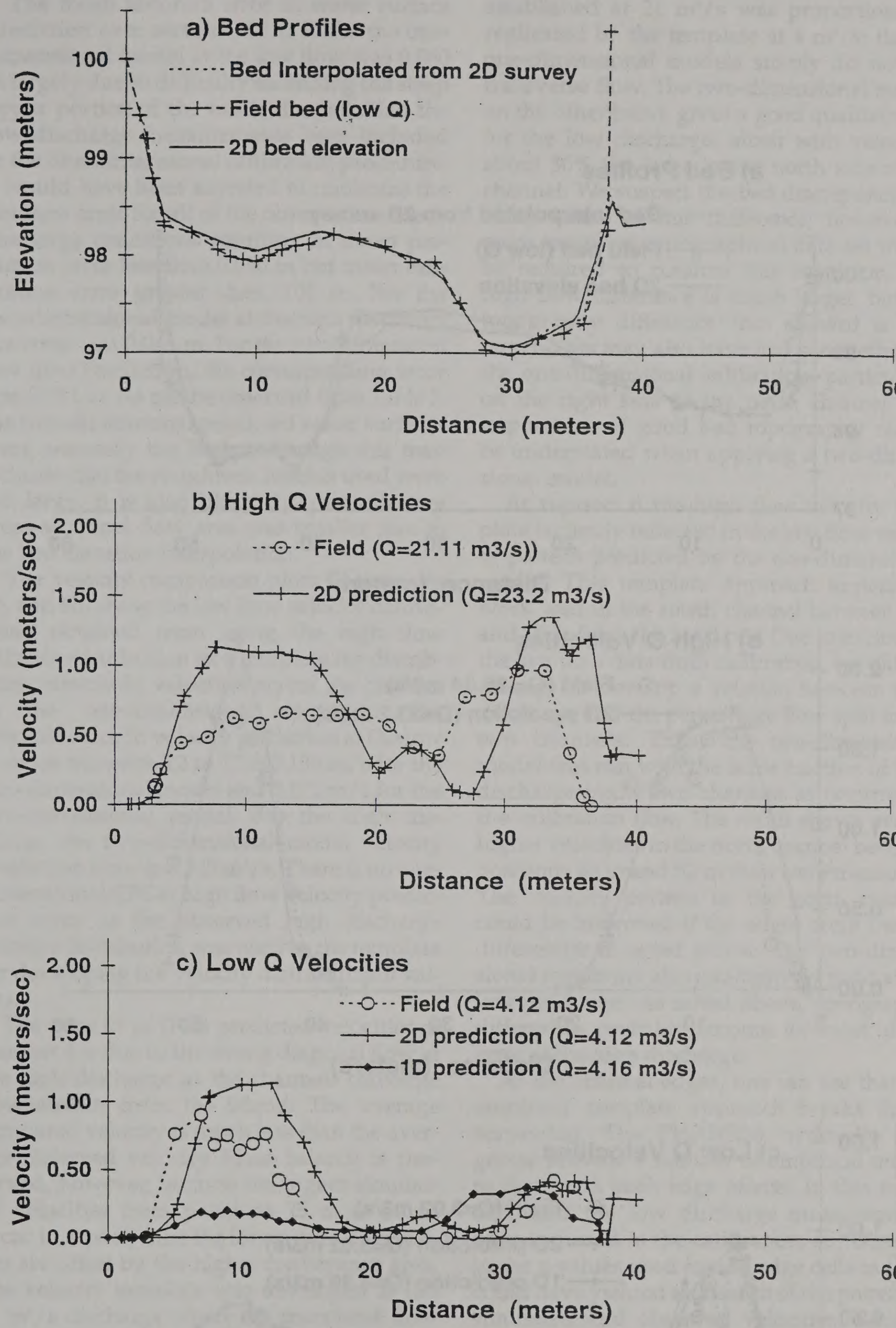

FIGURE 7. *Bed and velocity profiles for Transect 4.*

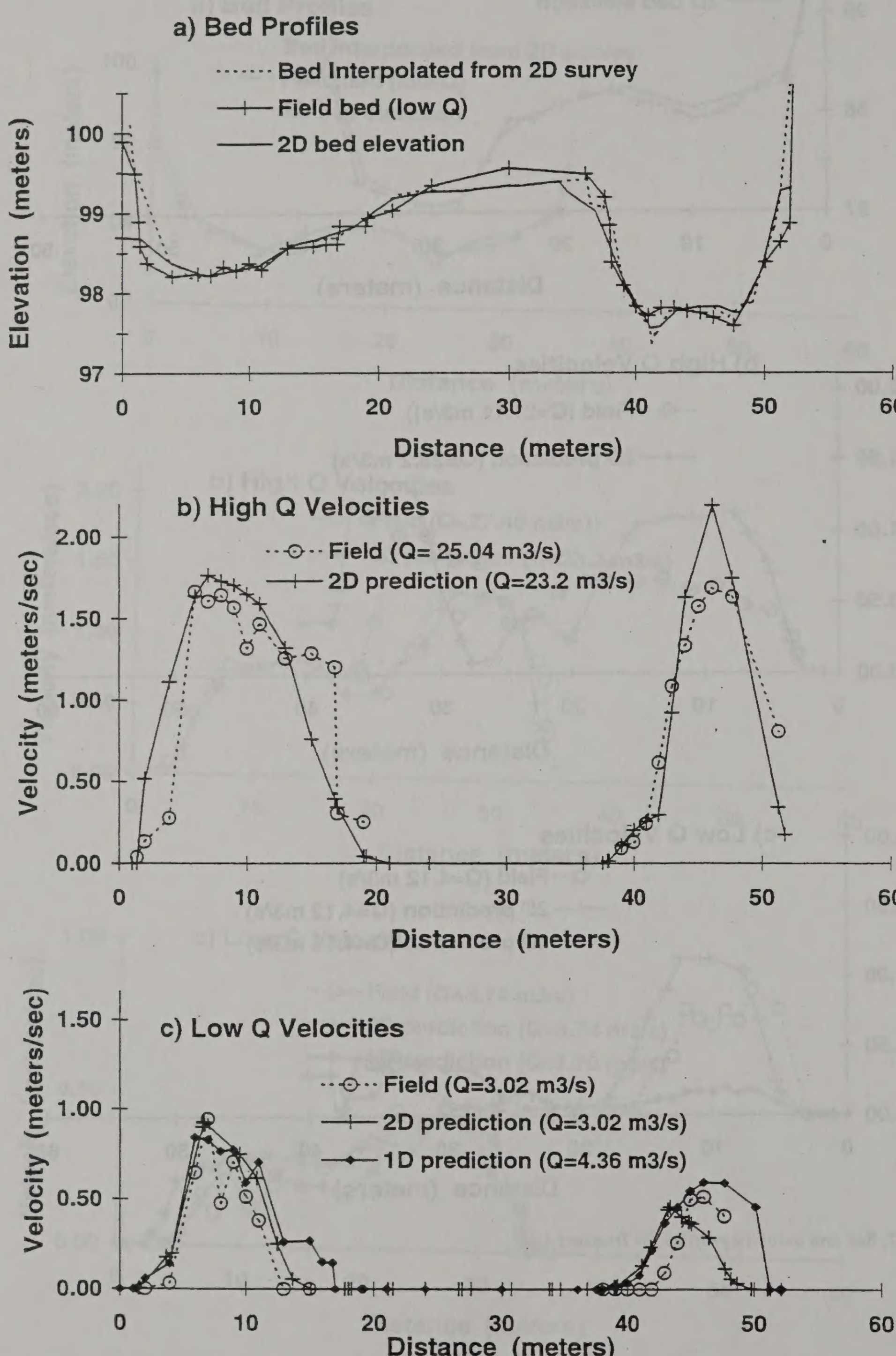

FIGURE 8. *Bed and velocity profiles for Transect 6.*

The mean absolute error in water surface prediction over sections T2 to T7 for the one-dimensional model at the low flow was 0.080 m largely due to difficulty ascending the steep upper portion of the north channel. Had the low discharge measurements been included in the one-dimensional calibration procedure, n would have been adjusted to minimize the absolute error for all of the observed transect-discharge conditions resulting in mean prediction error less than 0.080 m but mean calibration error greater than 0.01 m. For the two-dimensional model at the high discharge the error was 0.044 m. For the two-dimension low flow prediction, the corresponding error was 0.051 m. As can be observed from Table 2, the two-dimensional predicted water surfaces were generally too high. Although this may indicate that the roughness heights used were too large, it is also likely that the effective cross-sectional flow area was smaller due to the bed elevation interpolation.

The velocity comparison plots (Figures 6b, 7b, and 8b) show the low flow velocity distribution obtained from using the high flow velocity distribution as a template for distributing simulated velocities across the channel in the one-dimensional approach. The absolute error in velocity prediction at the low flow for transects T2 to T7 is 0.196 m/s for the one-dimensional model and 0.172 m/s for the two-dimensional model. For the high discharge the two-dimensional model velocity prediction error is 0.245 m^3/s. There is no one-dimensional (IFG4) high flow velocity prediction error as the observed high discharge velocity distribution was used as the template for developing the velocity distribution n values.

The poor fit of IFG4 predicted velocities at transect 4 is due to the strong diagonal flow at the high discharge as the channels converge downstream from the island. The average simulated velocity is much less than the average observed velocity. Mass balance is preserved, however, because the higher simulated velocities from positions 25 m to 37 m occur in a pool; thus the lower overall velocities are offset by the higher conveyance area. The velocity template was developed at the 21 m^3/s discharge where the transverse flow was well-established. At 4 m^3/s the bar representing the downstream end of the island presented significant resistance to transverse flow. The empirical velocity distribution established at 21 m^3/s was proportionately replicated by the template at 4 m^3/s; that is, one-dimensional models simply do not see transverse flow. The two-dimensional model, on the other hand, gives a good qualitative fit for the low discharge, albeit with velocities about 30% too large in the north side of the channel. We suspect the bed discrepancy is a likely cause of this difference; however, a more extensive topographical data set would be required to confirm this suspicion. The high flow difference is much larger, but the topography difference (not shown) is also larger. This may also have had some effect on the one-dimensional calibration, particularly on the right side of the north channel. The importance of good bed topography cannot be understated when applying a two-dimensional model.

At transect 6 the high flow velocity template is clearly reflected in the low flow velocity pattern predicted by the one-dimensional model. This template approach appears to work well in the south channel between 5 m and 15 m from the head pin. Due to excluding the low flow data from calibration, we did not attempt to develop a relation between total discharge and the percentage flow split in the two channels. Thus, the one-dimensional model was run with the same fraction of total discharge in the two channels as occurred at the calibration flow. The result shows overall higher velocities in the north channel between positions 40 m and 52 m than were measured. The velocity pattern in the north channel could be improved if the edges were treated differently as noted below. The two-dimensional results are also qualitatively good at the low discharge. As noted above, topographic differences probably account for most of the error at the high discharge.

At the channel edges, one can see that the empirical template approach breaks down somewhat. The PHABSIM hydraulic programs provide a number of empirical means to deal with such edge effects. In this situation, had the low discharge measurements been included in the calibration, adjustments to the n values used for the edge cells in IFG4 could have yielded a closer fit of the pattern of simulated and observed velocities. Because mass balance is maintained for each cross section, the effect of reducing edge velocities would be to increase velocities at the other points on the cross section.

DISCUSSION AND CONCLUSIONS

Our original purpose in this study was to perform a practical comparison of the accuracy of the one- dimensional and two-dimensional classes of hydrodynamic models in a hydraulically complex section of river with significant habitat value. Thus, we sought an area where data from an existing habitat study was available. This data provided even more of a real world test of the models than originally envisioned.

The data difficulties encountered in this study–channel change, unsteady flow, depth estimation noise, inundation of headpins, and the like–are typical of problems encountered in acquiring field data. The limitations imposed by this data and by insistence that one of the two sets of observations be excluded from calibration to provide a blind comparison cannot help but influence our findings. The large differences between observed and two-dimensional simulated velocities at transects 4 and 6 at the higher discharge likely result from two phenomena. The two-dimensional field data are relatively coarsely sampled compared to variations in the bed and the two-dimensional model roughness was not explicitly adjusted to calibrate precisely to observed water surface elevation. Finer sampling of the bed profile in the north channel and calibration adjustments of roughness heights in that area would likely improve the velocity profile fit.

Even with the data limitations encountered, we conclude that where the flow is essentially one-dimensional, both two-dimensional and the existing one-dimensional procedures can give comparable predictions. Where the flow exhibits significant lateral mass transfers, which vary with discharge, only the two-dimensional model can give an accurate prediction.

Like any empirical approach, data collected from a broad set of discharge conditions for the study stream or experience in making assumptions about those conditions are required to produce the best results with one-dimensional models such as those contained in the PHABSIM library. Thus, the quality of each application of these models is determined by a combination of data availability and user skill. The data collection for the PHABSIM study was performed by a different group than was the two-dimensional topographic data collection. The different project purposes and the difficulty in comparing the skill level of team members makes it impossible to give an objective comparative estimate of the time and effort required to apply the two types of model based on this experience.

The outcome of this study begs a rigorous comparison of the two methods. Our attempt to use two different data sets collected for different purposes at different times provided numerous lessons that are described below. To obtain a rigorous comparison, the data needs to be collected simultaneously for both model genres. The topographical data collected for the two-dimensional model should be collected at a greater density following breaks in the topography, and great care needs to be taken in collecting velocity and water surface profile measurements to account for unsteady flow. Calibration of the two-dimensional model using roughness heights and possibly the eddy viscosity coefficient would have led to improved results. However, the true sources of error may also include coarse bed elevation interpolation and a coarse computational mesh in shallow flow areas with nearby high velocity flow. Lastly, rigorous comparison of the two methods will also depend on comparable skill of the practitioners applying each of the models.

Implications for Habitat Studies

This study is only one example, but it suggests that there are some situations where the flow configuration in the channel is not well captured by one-dimensional models; for example, transect 4. It also suggests that some situations like transect 6 can be simulated comparably with a one-dimensional approach as with a two-dimensional approach if the division of flow between the two channels is known. From a habitat simulation standpoint, what does this mean?

Whether based on one-dimensional or two-dimensional flow models, the sensitivity of calculated habitat to errors in predicted depth and velocity ultimately depends on the form of the suitability criteria model used to transform hydraulic conditions into habitat values. From a habitat standpoint, changes in depth (resulting from water surface elevation simulation errors) of more than 5 cm may cause significant changes in calculated amounts of

usable habitat, depending on the sensitivity of target species' habitat preferences to depth. Experience suggests that habitat outcomes are even more sensitive to velocity than to depth. Thus, the more accurately either type of model predicts depth and velocity the more accurate the habitat representation. That is, the quality of the flow model application may be as important as the form of the model.

When critical habitat areas lie in hydraulic conditions that one-dimensional models do not handle well, such as eddies, transverse flow, and split flow, the two-dimensional approach will yield a clearly superior representation of the flow in those areas. Thus, with diverging or converging flow, eddies, intermittent backwaters, and split flows around islands, the ability of the two-dimensional models to represent conditions that the one-dimensional models can only "see" poorly represents a significant benefit in accuracy. However, when critical habitats lie in channels where streamlines are generally parallel to the channel, the precision of velocity simulation may be comparable between the two models. In areas with generally straight or gradually bending single channels the one-dimensional approach may suffice. Data limits or operator skill may be more of a factor than model type in such simple situations.

The effect of using different models on the final instream flow needs assessment is yet to be established. The next phase planned for this research will compare two-dimensional and one-dimensional approaches on a complete habitat simulation over a wide range of discharges.

Lessons In Data Collection

For the one-dimensional models, the fixed bed assumption imposes a major data collection burden. The user must be confident that the bed has not changed significantly. Experience accumulated at the MESC suggests that use of a wading rod to determine bed elevations can introduce 3 cm or more of bed measurement error. Therefore, in a wadable river, it is best to measure the bed with surveying instruments rather than as depth readings from a wading rod. Not only is the assumption of a flat water surface required, the size of the foot on the wading rod compared to the point on a prism pole can introduce discrepancies between two measurements taken at the same location.

In this study, it would have saved time to know the incremental rate of change of the unsteady flow observed. When unsteady flow occurs in the field, a record of the times with most measurements–especially the times of each velocity and water surface measurement–can be quite helpful in later analysis. Times were recorded at the beginning and end of each transect, but even more frequent time records would be helpful.

Because one can never predict discharge with certainty, it pays to place transect ends and high points defining banks higher than any anticipated flow. This will help avoid the possible introduction of error when survey markers, such as head pins, are inundated.

For two-dimensional modeling, a detailed and accurate topographic representation is essential. Obtaining as many closely spaced topographic measurements as time and resources allow will undoubtedly improve the final quality of a two-dimensional flow simulation. Topographic features such as banks and bars should be delineated carefully. The linear sequence should be retained to aid in subsequent interpolation. Generally, data collected in longitudinal patterns, following rough visual contour lines (breaklines), combined with cross-sectional data are probably the best. Such data can be introduced to the computational tools used to define bed topography as connected breaklines and thus preserve the patterns found in the field. Introduction of additional breaklines in the subsequent interpolation process appears to be essential to avoid introducing topographic features that are artifacts of the triangulation process.

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MesoHABSIM:
A concept for application of instream flow models in river restoration planning

ABSTRACT

This paper describes the methodological concept for application of physical habitat models to restoration planning at a whole river scale. The design proposed here builds upon the Instream Flow Incremental Methodology but is focused at the need for managing large-scale habitats and river systems. It modifies the data acquisition technique and analytical resolution of standard approaches, changing the scale of physical parameters and biological response assessment from micro- to meso-scale. In terms of technological process, a highly detailed microhabitat survey of a few, short sampling sites would be replaced by mesohabitat mapping of whole-river sections. As with more traditional stream habitat models, the variation in the spatial distribution and amount of mesohabitats can provide key information on habitat quality changes corresponding to alterations in flow, channel changes, and stream improvement measures. However, the scale of simulations more closely matches restoration and system analyses, because it provides a solid base for quantitative assessment and simulation of habitat conditions for the whole stream.

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Introduction

River restoration planning demands tools capable of quantifying the consequences of flow and channel modification at various temporal and spatial scales (Naiman et al. 1995). Such tools do not yet exist, but methods like Physical HABitat SIMulation model (PHABSIM) could fulfill this task. However, several issues need to be considered and resolved before instream habitat simulations can be applied for river restoration planning.

PHABSIM was developed in the early 1970s as a planning instrument for negotiations of in- and out-of-stream water use within the framework of the Instream Flow Incremental Methodology (Stalnaker 1995). This technique was originally designed for applications related to individual water use facilities and especially the definition of minimum flow requirements. PHABSIM and other related techniques use high precision measurements of physical conditions to predict flow-based alteration of habitat, together with habitat suitability data for fish. The underlying approach of PHABSIM is to describe these changes with a deterministic hydraulic model, originally developed for flood-control engineering. The choice of this hydraulic technique as the backbone of PHABSIM has been crucial to the entire process and, from a river-scale restoration perspective, a limitation of the model. Still commonly used, a one-dimensional model simplifies low-flow hydraulic conditions because it assumes steady, gradually varied, unidirectional flow (Gordon et al. 1992). The format of the algorithm determines the strategy for sampling channel morphology and hydraulics. Stratified sampling (i.e., transects) typically applied for this purpose is relatively crude and does not properly reflect the curvilinear distribution of hydro-morphologic parameters (LeCoarer and Dumont 1995; Parasiewicz et al. 1999a). Lately, multidimensional hydraulic models have been introduced that incorporate more comprehensive sampling techniques (e.g., Alfredsen et al. 1997). These methods reduce inaccuracy but still do not resolve the problem of high sensitivity of deterministic models to bed roughness, which is particularly critical when calculating low flows. Consequently, high resolution sampling of the bed form is the primary requirement. In more complex systems or where study objectives require habitat assessment in larger areas, the amount of necessary effort makes the application of such models impractical.

To limit the effort to a feasible level in larger scale applications, physical attributes used for model calibration are commonly measured at only a few short sampling sites, and model predictions are then extrapolated to larger segments of rivers and streams. Sometimes, this "representative site" design is supported by rapid habitat mapping to weight the spatial distribution of habitat features. Nevertheless, the accuracy of a river-wide assessment strongly declines during the extrapolation procedure due to variations in stream morphology among sampled sites (Dolloff et al. 1997), and the validity of habitat simulations may depend on the choice of sample locations (e.g., Gore and Nestler 1988; Williams 1996). For all these reasons, physical habitat models frequently are only marginally

applicable to large-scale issues and therefore inadequate for system-scale, holistic management.

Another debated aspect of common methods for habitat analysis is the spatial scale of the biological criteria. To merge hydraulic and biological models into a single habitat model, the spatio-temporal resolution of both must match. The observation of fish in microhabitats that are well within the immediate mobility range is largely coincidental. This introduces an error that can be reduced in part by increasing sample size. In larger spatial units, where the animals can be surrounded and captured, the observations are more conclusive. We believe that habitat and fish measurements at larger spatial units would be more practical, more relevant to large scale of management needs, and more conducive to habitat modeling (Hawkins et al. 1993).

In the last few years, alternative physical habitat models have been introduced, improved sampling methods have emerged, and multidimensional hydraulic and ecological models have been proposed (Parasiewicz and Dunbar 2001). Significant effort also has been invested to characterize geomorphologic units or habitat types at scales larger than the micro level (e.g., Hawkins et al. 1993; Jovett 1993; Vadas and Orth 1998). Although numerous studies have reported microhabitat criteria for a wide range of species and life stages, some habitat investigations have pooled microhabitat data to identify community-level habitat-use patterns. Lobb and Orth (1991) identified four key habitat types supporting the fish fauna of a stream. Aadland (1993) identified six habitat types such as pools and runs. Bain (1995) and Bain and Knight (1996) identified five key habitats that supported the greatest diversity and numbers of stream fishes. These and other studies defined meso-scale habitats by analyzing microscale habitat-use data. Another series of investigations (Bain et al. 1988; Kinsolving and Bain 1993; Travnichek et al. 1995; Bowen at al. 1998; Freeman et al. 2000), again using microscale measurements, identified the central role of shallow-water habitat in supporting stream fishes and explaining responses of communities to river regulation (reviewed in Bain and Travnichek 2000). These findings demonstrate that fish-habitat data at the mesoscale are relevant for river management, impact assessment, and fish conservation. Even when microscale data are collected at greater cost and difficulty, investigators and managers have found that results are most easily presented and used at the mesoscale. Finally, simulation of stream fish habitat conditions has been accomplished at the scale above the micro level (Layher and Brunson 1992; Lamouroux et al. 1998).

Here, I present a new concept for handling the physical side of stream fish-habitat relations and a modeling format that will accommodate biological data collection at a scale that is relevant to management. This article describes the methodological concept of a MesoHABitat SIMulation (MesoHABSIM) system that brings habitat simulation to a mesohabitat level by setting the precision of hydraulic sampling to larger units and increasing emphasis of system scale mapping. MesoHABSIM is primarily designed as a method applicable to streams and small rivers, although the general principles are also valid for larger rivers.

The concept

The primary objective of this concept is to promote development and application of habitat assessment procedures that are capable of being incorporated into large frameworks for river restoration. The system should adapt existing techniques to complement methods used to assess ecological integrity (Karr 1981; Muhar and Jungwirth 1998; Jungwirth et al. 2000). We use the mesohabitat approach of Bisson et al. (1982) in the central part of the habitat assessment procedure. Instead of intensively sampling a few representative sites, the survey of physical habitat

Table 1: Definitions of defined mesohabitat types (modified from Bisson and Montgomery 1996 and from Dolloff et al. 1993)

Mesohabitat type	Description
Riffle	Shallow stream reaches with moderate current velocity, some surface turbulence and higher gradient. Convex streambed shape.
Rapid	Higher gradient reaches with faster current velocity, coarser substrate, and more surface turbulence. Convex streambed shape.
Cascade	Stepped rapids with very small pools behind boulders and small waterfalls.
Glide	Moderately shallow stream channels with laminar flow, lacking pronounced turbulence. Flat streambed shape.
Run	Monotone stream channels with well determined thalweg. Streambed is longitudinally flat and laterally concave shaped.
Fast run	Uniform fast flowing stream channels.
Pool	Deep water impounded by a channel blockage or partial channel obstruction. Slow here. Concave streambed shape.
Plunge pool	Where main flow passes over a complete channel obstruction and drops vertically to scour the streambed.
Backwater	Slack areas along channel margins, caused by eddies behind obstructions.
Side arm	Channels around the islands, smaller than half river width, frequently at different elevation than main channel.

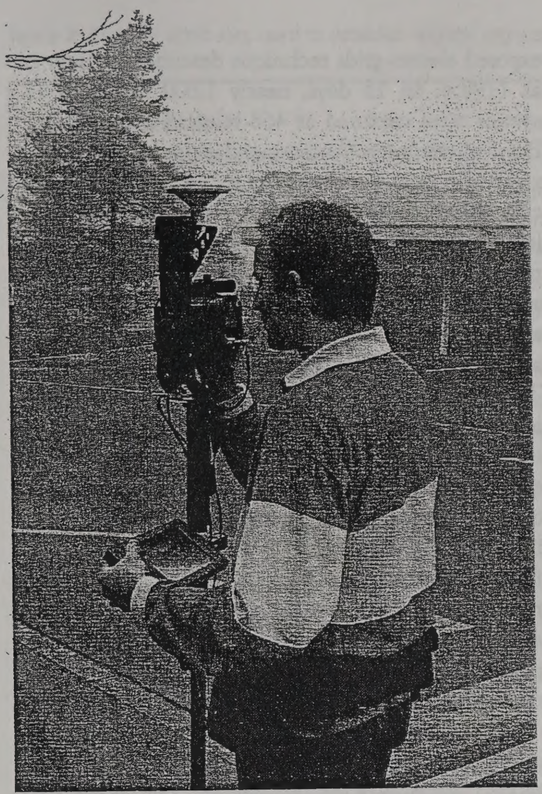


Figure 1. Survey equipment used for habitat mapping consisting of GAC field computer (in the belt), touch pen screen, laser range finder, and real time. The actual position, together with distant locations measured with range finder are plotted on uploaded aerial photograph on the screen, in the hand of Partick Lathion from Geo-Astor AG.

should determine the spatial extent of mesohabitats in the study area under multiple flow conditions.

As described by Hildebrand et al. (1999), habitat sequences often change with discharge level. It is broadly accepted that as flow rises, the distribution of hydro-morphological units will change from riffle-pool towards homogenous run-type habitat (Dunne and Leopold 1978). Hence, the standard hydraulic model can be substituted by quantification of changes in distribution of hydro-morphological units.

For mesohabitat classification, we propose the following hierarchical approach. The reach classification system (Montgomery and Buffington 1893; Arend 1999) is refined to identify high-, moderate-, and low-gradient sub-reaches. Within this framework, the modified and combined systems of Bisson and Montgomery (1996) and Dolloff et al. (1993) can be applied. The hydro-morphological units defined in Table 1 describe spatial arrangement of hydraulic attributes (otherwise determined with transects). This element combined with general notion of magnitude of depth and velocity, and presence of cover parameters, defines mesohabitat type. The number of possible combinations is large and there might be many more mesohabitat types than hydro-morphological units. Their identification is inconsequential because species-specific habitat suitability is the only matter that counts in modeling.

In wadable streams, the spatial extent of individual mesohabitats can be estimated during "river hike," using a combination of aerial photographs, a laser range finder, and a field computer. In addition to describing the size and type each hydro-morphological unit, the extent of cover such as shading, shoreline sinupsity (a function of shore line and river length), and shallow margins are estimated. Random sampling techniques can be applied to obtain the key hydraulic characteristics of the unit. The quantitative distribution of depth, mean column velocity, bottom velocity, and substrate together with secondary attributes like maximum, mean, variance, and Froude number are then used to describe mesohabitats.

Mesohabitat-level biological criteria, even for whole communities, can be relatively easily defined with standard methods (Lobb and Orth 1991; Aadland 1993; Freeman et al. 2000). Multivariate statistics and ecological metrics can be used for habitat quality assessment. Logistic regression is a very powerful tool for this purpose (Guay et al. 1999, Parasiewicz et al. 1999a,b). Established criteria used to describe the suitability of each combination of physical attributes for individual species or whole communities and can be expressed in various forms. The probability of fish presence can be computed from regression equations. The quality of a section or reach of river can be defined by quantifying habitat areas with probabilities higher than 50% at different flows. Another possibility is the use of a normalized suitability index as in PHABSIM. The areas of various mesohabitats occurring at measured flow conditions are weighted by the index and summarized over selected segments or the whole study site. Yet another possibility is the use of landscape metrics like heterogeneity, patchiness, etc. (as in McGarigal and Marks 1995; McGarigal and McComb1995, 1995). Habitat rating curves for specified units can be constructed by plotting suitable habitat area or weighted usable area, or landscape metrics against discharge. This part of the procedure differs from PHABSIM because the rating curves are established for the whole study area.

Biological response to individual restoration measures will be simulated by manipulating the quantity or quality of mesohabitats and temporal or spatial variation of flow. Habitat time-series analyses can be applied to the whole river or selected sections. Restoration scenarios can be simulated to predict the influence of dam removals, enhanced flow regimes, and channel reconstruction on sequences of mesohabitat types and also overall stream habitat quality.

Example of application

The biggest uncertainty associated with this concept is the feasibility and adequacy of data sampling procedure. The previously described method was applied during a river restoration study on the

Quinebaug River, MA and CT. The validity of the assumptions was proved in many cases, and preliminary results are presented to verify the concept discussed above.

The Quinebaug River is a fourth order river with multiple impoundments and a history of industrial use. The river is highly heterogeneous with contrasting gradient and flow conditions. In general, the river is difficult to wade due to cobble, woody debris, and dark "marshy" water.

During the MesoHABSIM survey conducted in summer and fall 2000, 38 km of the river were mapped at low flow with equipment provided by GeoAstor AG (Figure 1). On average, a three person team covered one km per day. After the first survey, the river was delineated into 11 contiguous sections based upon macro scale characteristics (gradient, flow, dominant substrate, cover, etc.). Sensitivity analysis of quantitative distribution of hydro-morphological units was used to identify the shortest representative sites for each section. The sites (combined length—9.2 km) were then surveyed at three different flow releases (0.6 m^3/s, 1.1 m^3/s, and 2.0 m^3/s—regulated at the uppermost dam) (example in Figure 2).

Biological criteria were established with the pre-exposed electro-grids technique described by Bain et al. (1985). In 15 days, nearly 1,800 fish from 17 species were captured at 468 selected mesohabitats. Physical attributes (hydro-morphological unit, cover, and hydraulics) were recorded for each sample. Cross correlation analysis was used to exclude highly correlated parameters and we used stepwise forward logistic regression to identify suitable habitat. Initially, regression analysis was completed for two contrasting species: bluegill (*Leptomis macrochirus*)—a generalist, and fallfish (*Semotilus corporalis*)—a fluvial specialist. The models had high predictive value (>75%) and accurately reflected known biological behavior of these species (Table 3). Bain and Meixler (2000) defined five species (fallfish, common shiner *Luxilus cornutus*, white sucker *Catostomus commersoni*, longnose dace *Rhininchtys cataractae*, and blacknose dace *Rhininchtys atratulus*) that dominated the target community, and these species were analyzed next. The regression equations were then used to determine the probability of fish presence in mesohabitats mapped during the survey of representative sites (Figure 3).

The proportion of wetted area with fish-presence probabilities higher than 50% was summarized and plotted against flow during sampling. The curve-fitted rating curves are assumed to be valid not only for the

Figure 2. Spatial distribution of hydro-morphological units measured in site 4 of the Quinebaug river during 0.6 m^3/s (top), 1.1 m^3/s (middle) and 2 m^3/s (bottom) release from East Brimfield Lake.

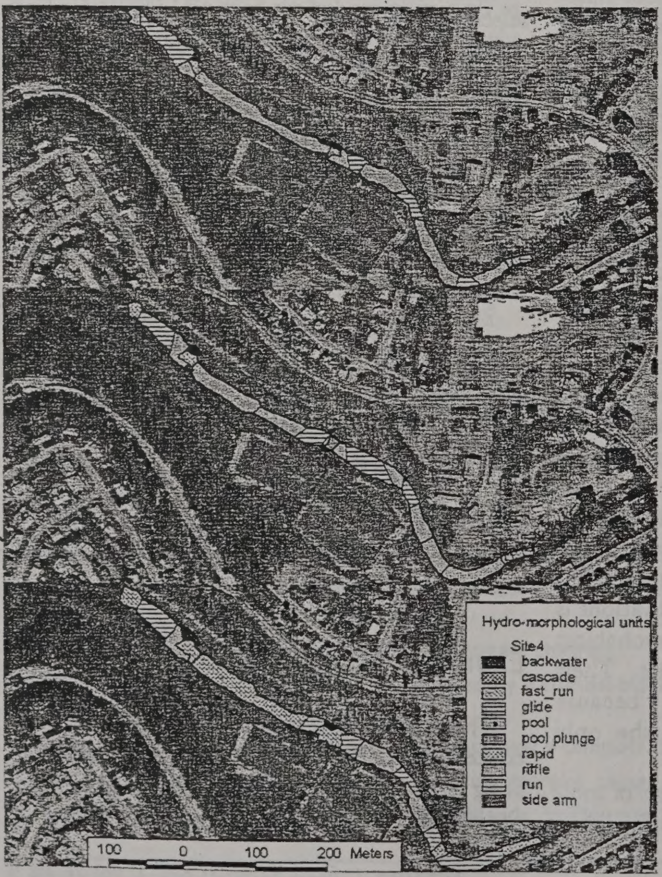


Figure 3. The spatial distribution of habitat suitable for selected community indicating number of supported species.

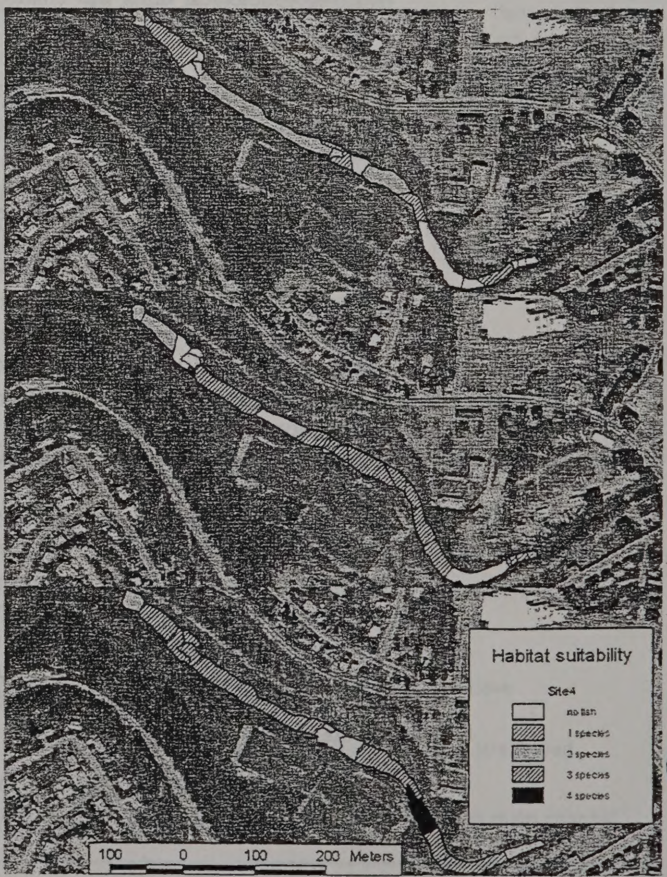


Table 2: Physical attributes used to establish logistic regression with fish absence and presence.

Attribute (value)	
Categories of Hydro-morphological units (yes/no)	(see table 1)
Cover sources (no/some/much)	Undercut bank, woody debris, overhanging vegetation, submerged vegetation, boulder, riprap, canopy cover shading, shallow margin
Choriotop (% of random samples)	Pelal, psamal, akal, micro-lithal, meso-lithal, macro-lithal, mega-lithal, phytal, xylal, sapropel, detritus (for exact definitions see Austrian Standard ON6232)
Depth (% of random samples)	6 classes in 25 cm increments (range 0–125 cm and above)
Mean column velocity (% of random samples)	8 classes in 15 cm/s increments (range 0–105 cm/s and above)
Froude number	Average

representative sites but for the entire sections. The ratio of representative length to section length was used as a weighting factor for each rating curve constructing a composite rating curve for the whole 38 km long study site (Figure 4). This provided the assessment tool for simulation of various management options such as temporal and spatial manipulation of flows as well as improvements of the riverbed structure.

This study is beginning a second year of data collection and detailed results will be published in the future. Nevertheless, preliminary results definitively prove the feasibility of the concept.

Conclusions and discussion

We have developed a theoretical concept of modeling a river system using physical habitat simulation such as PHABSIM performed at a mesoscale of resolution. This system enhances a widely recognized technique, emphasizes biological requirements for modeling, and includes large scale spatial coverage. It permits quantitative evaluation of management scenarios from the perspective of the aquatic community in the entire river.

The possibility of cross scale analysis that closes the gap between macro- and micro-scale approaches is among the greatest benefit of this approach. In the long run it could provide a way to quantify specific biological response to changes of macro-habitat attributes, for example by coupling indicators of hydrological alteration (Richter et al. 1997) with habitat.

It needs to be emphasized that application of MesoHABSIM is not limited to minimum flow studies, but also allows for predictive assessment of wide range of restoration measures including channel improvements and dam removals. For example, the replacement of the impounded section in the model with the expected habitat mosaic will change the shape of the habitat-flow rating curve and allow for conclusions about ecological benefits prior to demolishing the dam.

The procedural benefits

Mesohabitat scale precision is more efficient for sampling biological data. Species can be captured within the range of their diurnal mobility, thereby reducing bias introduced by temporal and behavioral aspects. For the same reason, the method is better for evaluation. The criteria can be established for individual species as well as for whole communities. Quantitative assessment of prediction validity is an important instrument in adaptive management practice.

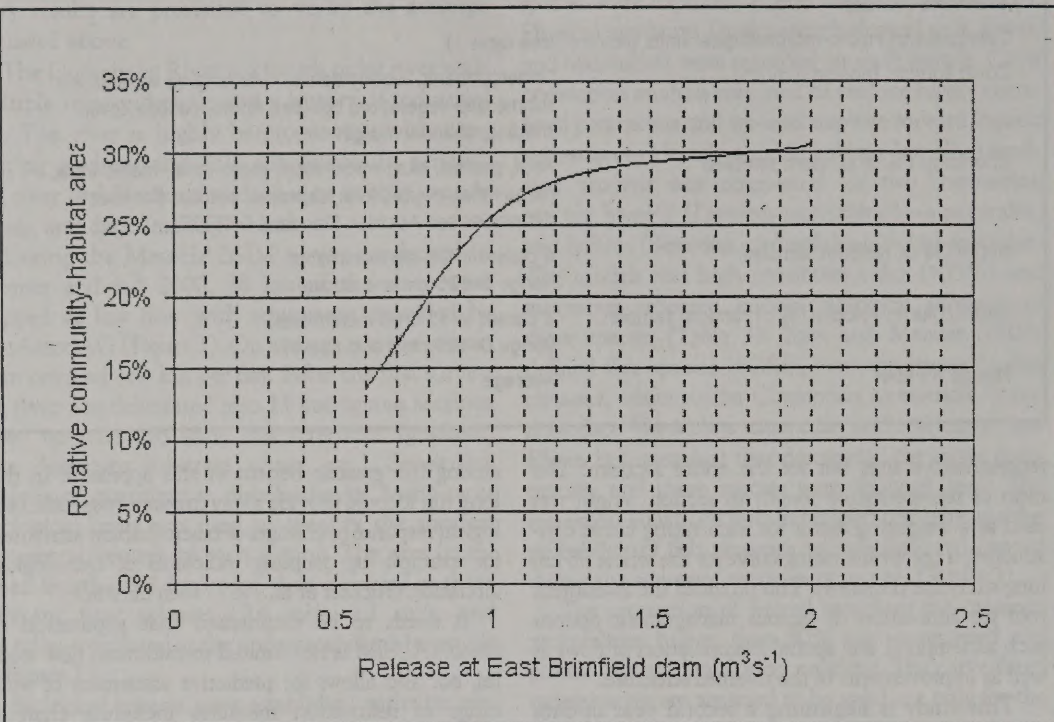
The process of generalizing the results from representative sites to the whole study area is supported by quantitative analysis of habitat distribution. This increases the accuracy of overall assessment due to the reduction of "second-stage sampling error" (i.e., error among the sampling sites, Hankin 1984) and provides sound input for larger scale GIS analysis. This opens new analytical possibilities for combining spatial and ecological metrics with biological response.

The example showed that the technique is effective and provides reasonable results. Within observed flow range, the sensitivity of mesohabitat distribution to flow alteration was greater than expected.

Table 3: The results of regression calculation for bluegill and fallfish. The table shows significant habitat attributes and their beta coefficients. Positive numbers indicate positive reaction and vice versa.

Bluegill		Fallfish	
Attribute	Beta	Attribute	Beta
Velocity 15-30 m^3/s	2.02	Boulder	1.95
Shading	1.05	Shading	-1.07
Glide	-2.19	Depth 0-25 m^3	-1.76
Velocity 30-45 m^3/s	1.07	Velocity 45-60 m^3/s	1.06
Submerged vegetation	-0.75	Run	-0.57

Figure 4. The rating curve of relative habitat area versus flow release for study area on Quinebaug River.

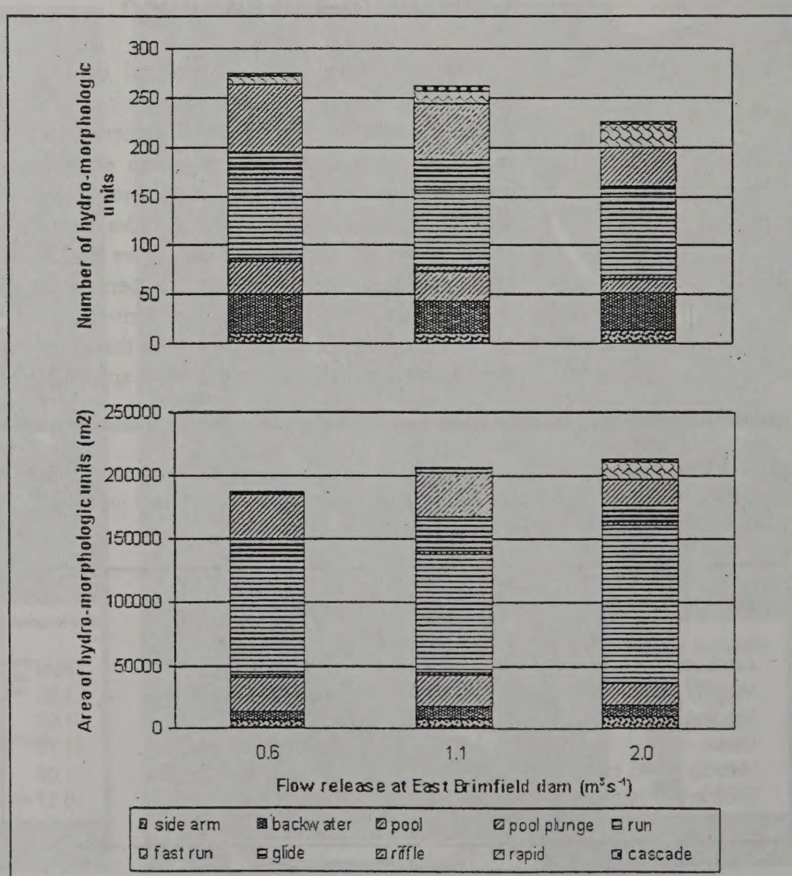


Interestingly, we observed more change in the types of mesohabitats than of their wetted area (see Figure 2). Another observation indicated that the number of hydro-morpholocial units declined (from 276 to 262 to 227) and the areas of run-type habitat increased as flow increased (Figure 5). This observation supports the previously stated expectation that habitat distribution is more uniform and should eventually turn into one dominated by fast runs at higher flows.

This result (also confirmed on two streams in the Catskill Mountains in New York State) suggests that the sampling technique could be simplified. For example, the initial mapping of the river that helps to select representative sites could be reduced to habitat counts only. Furthermore, at high flows mapping could be condensed to relatively crude estimates of habitat areas. The character of fast flowing runs that are frequent during higher flows is relatively uniform and for many species beyond the range of utilization. Detailed sampling might not be necessary to define the habitat suitability of these units. The hydraulic models can be also applied more effectively for high flows because fewer cross sections are needed to provide an accurate model. The remaining refuge areas should be much easier to sample.

The high flow technique has not been tested yet and the present model has proved valid only for relatively small streams at low flow conditions. Nevertheless, the potential for model extension to the different situations exists and is competitive with other existing approaches.

Figure 5. Quantitative distribution of hydro-morphological units at three investigated flow releases. The upper graph shows the changes in the unit numbers and lower in unit areas.



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Extended Abstract
7th Federal Interagency Sedimentation Conference, March 25-29, 2001, Reno, Nevada

FLOW REGIMES NEEDED TO MAINTAIN CHANNELS IN GRAVEL-BED RIVERS

Larry J. Schmidt, Program Manager, USDA Forest Service, Rocky Mountain Research Station, Stream Systems Technology Center, Fort Collins, CO
John P. Potyondy, Hydrologist, USDA Forest Service, Rocky Mountain Research Station, Stream Systems Technology Center, Fort Collins, CO

Abstract: A range of moderate to high flows that occur less than 20 percent of the year are effectively maintain the physical features of gravel-bed channels. The typical channel maintenance hydrograph includes a range of discharges making up a portion of the rising and falling limbs of the annual hydrograph. Consequently, the proposed maintenance flow regime begins at a discharge at which hydraulically limited gravels begin to move and includes all flows up to and including the instantaneous 25-year flow. Flows are needed for the duration during which they naturally occur. Flow rates that fail to exceed the threshold for hydraulically limited gravels are unnecessary for channel maintenance.

INTRODUCTION

Natural self-maintaining channels are a desirable feature of streams on the National Forest. In order to fulfill the primary National Forest purpose of "securing favorable conditions of water flows," the Forest Service seeks to establish non-consumptive channel maintenance instream flows. These flows, coupled with proper management of upland watersheds, will provide favorable conditions of water flows as intended by the Organic Act of 1897. After serving public needs on the National forests, all this streamflow becomes available to downstream users under state law to meet designated beneficial uses.

The Forest Service must retain essential instream flows that sustain streams because future offstream uses such as irrigation, municipal water supplies, or other legitimate uses may deplete these flows. When essential instream flow is removed, sediment accumulates in the channel because the reduced flows cannot transport the sediment load received. The channel responds by altering its size, morphology, meander pattern, rate of migration, streambed elevation, bed-material composition, floodplain morphology, and/or streamside vegetation. These channel adjustments are frequently detrimental to favorable fluvial and instream ecosystems. The channel adjustments and vegetation ingrowth can constrict the channel, resulting in more frequent inundation of the floodplain by high flows.

SUMMARY OF SCIENTIFIC BASIS

In developing this channel maintenance approach, we have applied current scientific knowledge and will continue to refine our approach as knowledge about flows and their relationship to ecosystems improves.

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SUMMARY OF SCIENTIFIC BASIS

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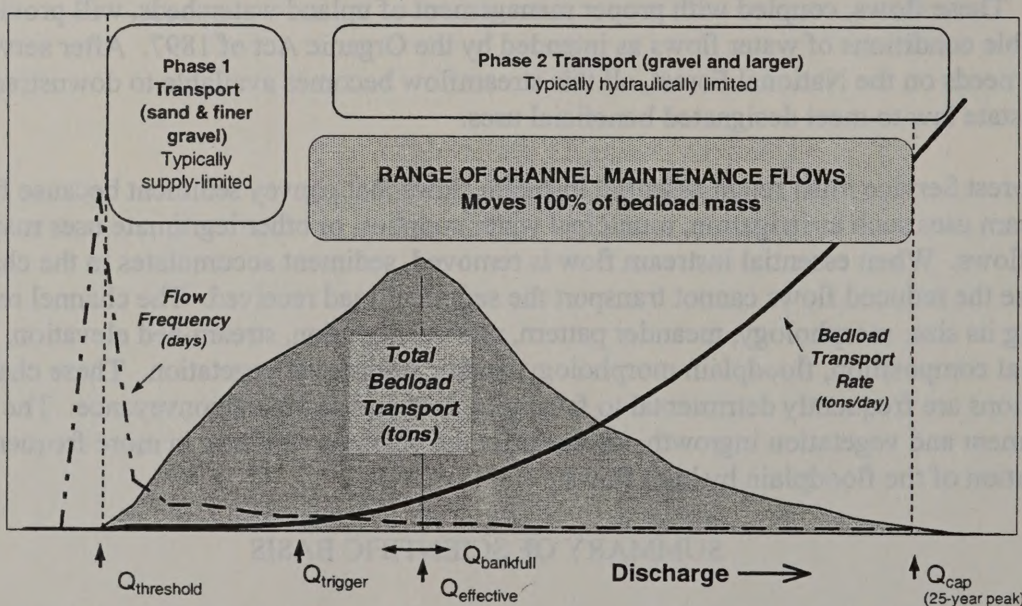
Sediment and vegetation have separate and combined influences on channel maintenance processes. The proposed approach has two major components: A bedload sediment transport component, and a streamside vegetation flow component.

The sediment transport component is required for every channel maintenance flow evaluation and is discussed here. The sediment transport component is primarily designed to move the required amount and sizes of sediment necessary to maintain channel capacity. Because these flows exceed bankfull stage, they may also scour vegetation from within the channel and periodically inundate portions of the floodplain thereby recharging aquifers and providing the disturbance required to sustain beneficial streamside vegetation. Generally, in temperate mountainous environments, where water accumulates at the base of slopes, the sediment transport component satisfies the vegetation regeneration and maintenance needs of streamside and floodplain vegetation.

The following figure illustrates the general model. The model requires streamflow and bedload transport data. The required instream flows begin with the initiation of Phase 2 bedload transport (Jackson and Beschta, 1982) up to the 25-year flow. A variety of techniques may be used to identify the beginning of Phase 2 transport including measured bedload samples, in-channel sediment traps, or analysis of bed material composition.

A General Model of Sediment Transport Processes for Channel Maintenance in Gravel-Bed Rivers



Extended Abstract
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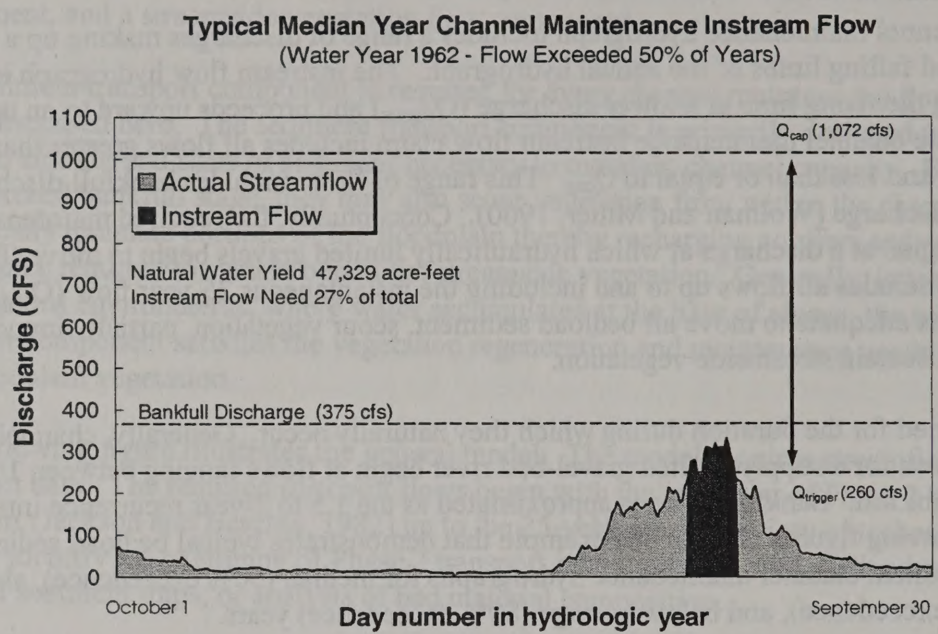
TYPICAL CHANNEL MAINTENANCE HYDROGRAPHS

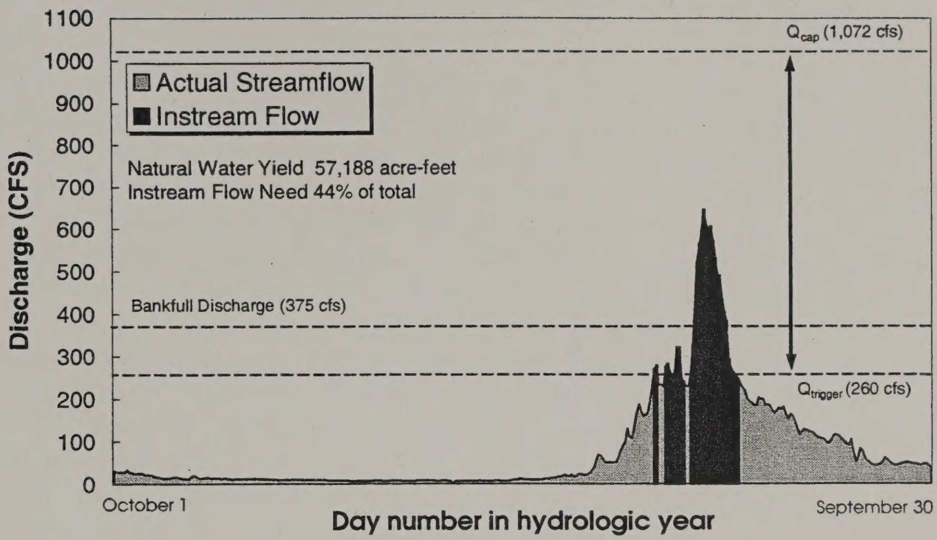
The typical channel maintenance hydrograph includes a range of discharges making up a portion of the rising and falling limbs of the annual hydrograph. The instream flow hydrograph is initiated during the rising limb at a lower discharge ($Q_{trigger}$) and proceeds upward to an upper limit (Q_{cap}). The channel maintenance instream flow claim includes all flows greater than or equal to $Q_{trigger}$ and less than or equal to Q_{cap}. This range of flows includes bankfull discharge and effective discharge (Wolman and Miller, 1960). Conceptually, the required maintenance flow regime begins at a discharge at which hydraulically limited gravels begin to move (Phase 2 transport) and includes all flows up to and including the instantaneous 25-year flow (Q_{cap}). This range of flows is adequate to move all bedload sediment, scour vegetation, partially inundate the floodplain, and sustain streamside vegetation.

Flows are claimed for the duration during which they naturally occur. Generally, channel maintaining flows for a supply-limited gravel-bed river begin at flows ranging between 1/2 bankfull and bankfull. Bankfull often is approximated as the 1.5 to 2-year recurrence interval flow. The following figures provide one example that demonstrates typical bedload sediment transport component channel maintenance hydrographs for median (50% exceedence), above average (20% exceedence), and below average (80% exceedence) years.

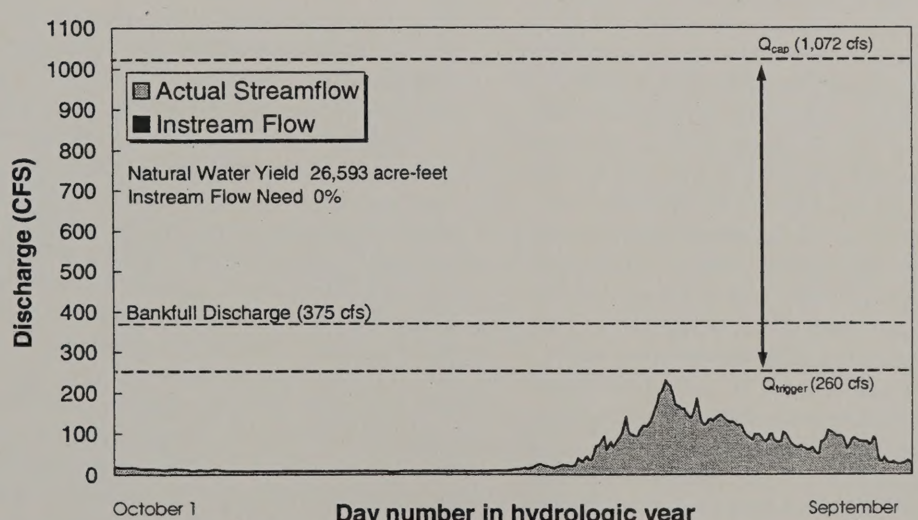
The figures illustrate that the volume of water required for channel maintenance is highly variable from year to year, averaging about 30 to 40 percent of the annual flow volume. Since channel-maintaining flows rely on flow near and above bankfull, a high percentage of channel maintenance water needs are satisfied during wet years. During many low flow years, little to no water is required for channel maintenance.


Typical Median Year Channel Maintenance Instream Flow
(Water Year 1962 - Flow Exceeded 50% of Years)
Actual Streamflow
Instream Flow
Natural Water Yield 47,329 acre-feet
Instream Flow Need 27% of total
Bankfull Discharge (375 cfs)
Qcap (1,072 cfs)
Qtrigger (260 cfs)
Discharge (CFS)
1100
1000
900
800
700
600
500
400
300
200
100
0
October 1
Day number in hydrologic year
September 30

Typical Above Average Channel Maintenance Instream Flow
(Water Year 1971 - Flows Exceeded 20% of Years)



Typical Below Average Channel Maintenance Instream Flow
(Water Year 1976 - Flows Exceeded 80% of Years)



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Ecosystem Restoration:

A Case Study in the Owens River Gorge, California

ABSTRACT

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A Case Study in the Owens River Gorge, California

By Mark T. Hill and William S. Platts

ABSTRACT

In 1991 the Los Angeles Department of Water and Power, in cooperation with Mono County, California, initiated a multiyear effort to restore the Owens River Gorge. The project aims to return the river channel, dewatered for more than 50 years, to a functional riverine-riparian ecosystem capable of supporting healthy brown trout and wildlife populations. The passive, or *natural*, restoration approach focused on the development of riparian habitat and channel complexity using incremental increases in pulse (freshet) and base flows. Increasing pulse and base flows resulted in establishment and rapid growth of riparian vegetation on all landforms, and the formation of good-quality microhabitat features (pools, runs, depth, and wetted width). An extremely complex, productive habitat now occupies the bottom lands of the Owens River Gorge. A healthy fishery in good condition has quickly developed in response to habitat improvement. Brown trout numbers have increased each year since initial stocking, 40% between 1996 and 1997. Catch rates increased from 0 fish/hr in 1991 to 5.8–7.1 fish/hr (with a maximum catch rate of 15.7 fish/hr) in 1996. Restoring the Owens River Gorge bridges the theoretical concepts developed by Kauffman et al. (1997) and the practical application of those concepts in a real-time restoration project.

The purpose of restoration is to shift ecosystems from a dysfunctional state to a functional state. A functional ecosystem exhibits self-sustaining natural processes and linkages among terrestrial, riparian, and aquatic components (Kauffman et al. 1997). In watershed-level ecosystems the riverine-riparian component plays a primary role by linking with terrestrial components to sustain total biodiversity, natural processes, and the movement of energy within and among watersheds (Stanford and Ward 1992). The lifeblood of the riverine-riparian system is the timing, quantity, and quality of flowing water, which influences quantity and quality of riparian habitat, fisheries and wildlife resources, and the way energy is transported among ecological components (Hill et al. 1991; Beschta 1997; Poff et al. 1997).

Restoring rivers is a linear process; riparian habitat strongly influences geomorphic processes and must develop ahead of in-channel habitat to maximize complexity and sustain habitat. The development of riparian systems is part of a directional sequence known as the *reversible process concept* (Amoros et al. 1987), within which the directional sequences are rejuvenated by erosion, deposition, and flood disturbance.

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Kauffman et al. (1997), in an overview of ecosystem restoration in the western United States, identify two primary causes of ecosystem dysfunction: land and water use practices. Watersheds affected by land use practices are those in which grazing and logging activities are improperly managed, while poor water use practices include stream diversion and flood control actions that degrade aquatic habitat. Kauffman et al. (1997) also identify several management strategies that correct degradation caused by land and water use activities but do not necessarily qualify as ecological restoration (i.e, preservation, creation, reclamation, rehabilitation, replacement, mitigation, and enhancement).

This paper presents a case study of riparian and stream restoration in the Owens River gorge that applies many of the concepts and approaches Kauffman et al. (1997) suggest. This empirical study shows that restoration can include most of the management strategies they identified. Our approach to restoring the gorge has used multiple flow regimes that are both *passive* (or *natural)* and *active* interventions (Kauffman et al. 1997).

During these initial years of restoration, incremental changes in annual pulse and base flows were used to establish riparian vegetation on landforms and develop complex habitat. This was the *active* phase of restoration and required manipulation of discharge from year to year. The *passive* restoration phase arrives when the river reaches functionality; final instream flows will then be established that sustain ecological processes. This passive phase also might be described as a *preservation*

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management strategy since the ecosystem would be intact and no additional diversion or dewatering would be allowed.

Restoration of the Owens River gorge has included management strategies that *create* additional wetlands, *reclaim* self-sustaining habitat to benefit endemic fish species, *rehabilitate* lost riverine-riparian vegetation types, *replace* native fish species with an exotic target species, *enhance* wetland habitat with the use of an historic stream barrier, and *mitigate* for hydropower generation. The associated study provides a bridge between theoretical concepts developed by Kauffman et al. (1997) and practical application of these concepts in a real-time restoration project.

Pre-restoration conditions in the Owens River Gorge

The Los Angeles Department of Water and Power, in cooperation with Mono County, is restoring the riverine-riparian ecosystem in the Owens River gorge, California (Figure 1). The river is bounded by Crowley Reservoir upstream and Pleasant Valley Reservoir downstream. The lower 16 km of the Owens River gorge (from the Upper Gorge power plant to the Control Gorge power plant) has been dewatered for hydroelectric purposes from 1953 to 1991, resulting in a dry river channel devoid of riparian vegetation and fish.

The Owens River gorge lies in a high desert plateau between the eastern Sierra Nevada Mountains to the west and the White Mountains to the east (Figure 1). The narrow, notched canyon has nearly vertical side walls averaging 240 meters high. Crowley Reservoir blocks sediment and gravel recruitment; colluvial inputs associated with infrequent landslides are the only source of new sediment material. The valley bottom is narrow in most places (<50 m) and widest (> 1,000 m) at the lower end, which is above the Control Gorge power plant. Gradient through the gorge averages 10 m/km. Because of its proximity to two mountain ranges, historic freshet flows in the gorge were extremely high and sudden. Historic flows have varied from more than 85 m^3/s in the spring to less than 5 m^3/s by late summer. Historic flows have created four principle landforms in the Owens River gorge: (1) terraces several meters above the streambed; (2) levees or incised streambanks; (3) floodplains adjacent to the channel; and (4) the channel itself.

A barrier placed in the river in the early 1950s just above the Control Gorge power plant to prevent fish migration from Pleasant Valley Reservoir into the fluctuating backwater areas also checks sediment movement and pooled flow from seeps and springs; this has resulted in a remnant wetland present throughout the half-century of dewatering.

Land uses that preceded water diversion for hydropower have included intensive mining, wood cutting, and livestock grazing. Early land use practices caused severe impacts to riparian vegetation and streambanks.

Prior to dewatering, the central feature of the Owens River gorge ecosystem was the riverine-riparian system. The riparian zone was dominated by willows (*Salix* spp.) and, to a lesser extent, by cottonwood (*Populus* spp.) and associated tules (*Scirpus* spp. and *Typha latifolia*). The remnant wetland was the key habitat feature that supported most of the biodiversity in the gorge. Small galleries of cottonwood and tree willow were maintained in the seepage downstream of the three power plants and in the remnant wetland during the years of dewatering. These small remnant populations of cottonwood and willow provided the seed source for restoration.

Endemic fish species in the gorge have included endangered Owens tui chub (*Gila bicolor snyderi*) and the Owens speckled dace (*Rhinichthys osculus* ssp.), a candidate for threatened or endangered species listing under the Endangered Species Act; both species still occur in the river, primarily in the wetlands at the lower end of the gorge and in the reach designated as critical habitat for tui chubs between Crowley Reservoir and the Upper Gorge power plant.

Restoration goals

Goals of the restoration project were to maintain power production, rewater the river, recreate riparian habitat, and reestablish a healthy fish population (Brodt and Pettijohn 1995). Although native fish populations could be reestablished in the Owens River gorge, the

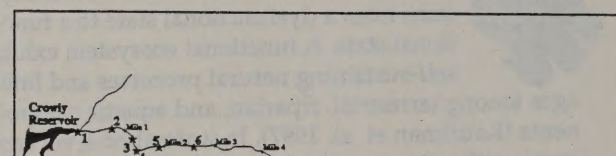

Figure 1 depicts the Owens River gorge, power plants, and sample sites by river mile.

California Department of Fish and Game selected brown trout (*Salmo trutta*) as the target species on which to build a healthy fishery. Regional and local emphasis on recreational fishing helped drive the decision for a brown trout fishery.

The primary objective in achieving these goals was the reestablishment of riparian habitat that functioned in concert with the river, wetlands, and upland habitats (i.e., the free energy exchange among habitats) by mimicking natural flow processes. Key to successful restoration in the Owens River gorge was development of riparian vegetation through good stream flow management.

Riparian areas in watersheds provide numerous ecological links between uplands and their aquatic ecosystems (Heede 1985; Gregory et al. 1991; Naiman et al. 1992) as well as create shade, cover, and organic debris (Large and Petts 1994). Riparian zones in the Owens River Gorge were the source of extremely important structural components of the aquatic ecosystem. Woody debris is often the dominant element in the physical structure of streams (Bisson et al. 1987), and when coarse, woody debris enters a stream, a critical role of the riparian forest is played (Swanson et al. 1976; Harmon et al. 1986; Maser et al. 1988). Riparian vegetation in the gorge also provided an important nutritional substrate for the aquatic ecosystem. Allochthonous inputs that dominate small streams are the main source of energy (Triska et al. 1982; Gregory et al. 1991). Riparian vegetation has been shown to exert significant control over fluvial processes and the determination of instream habitat via (1) flow resistance; (2) flow interruption by log jams; (3) interception and storage of sediment; (4) bank strengthening; and (5) concave bank bench deposition (Hicken 1984; Gregory and Gurnell 1988).

Disturbance regimes in stream ecosystems are important in shaping riparian zones and their vegetation (Gregory et al. 1991; Hill et al. 1991); establishing a disturbance regime was fundamental to recovering the Owens River Gorge. First and foremost, our method was to avoid mechanical intervention and provide the ecosystem with flows that allowed natural processes to occur. Passive or *natural* restoration must begin with flows that promote complex riverine-riparian habitat required to maintain a healthy fishery. Our approach was to allow riparian vegetation to respond to incremental increases in both base flows and pulse flows throughout many years before larger flows are permanently released in the gorge (Table 1). In the early stages of our efforts, we had to carefully match pulse flows with the ability of vegetation on landforms to trap and hold sediments. Due to Crowley Reservoir Dam, the gorge is starved for sediments, and the river system cannot afford to lose sediments necessary to build streambanks. Base flows in early stages of restoration had to match pulse flows to ensure that newly established riparian vegetation on landforms was maintained throughout the growing season.

Table 1 lists actual and target base and pulse flows in the Owens River Gorge from 1991 to 2000. (Target flows were established by agreement between Mono County and the Los Angeles Department of Water and Power).

Year	Base flow (cfs)		Pulse Flow (cfs)	
	Target	Actual	Target	Actual
1991	16	16	0	0
1992	16	16	0	0
1992	16	16	24	26
1994	16	16	24	32
1995	16	16	24	40
1996	26	26	39	60
1997	36	26	39	70
1998	46	36	69	90
1999	56	---	84	---
2000	65	---	98	---

Flow management

Reestablishment of the Owens River Gorge ecosystem was based on multiple stream flows that allowed natural processes to proceed for an extended time. Mechanical intervention such as pool digging, log placement, bank stabilization, and artificial plantings was possible, but such interventions are rarely successful (Beschta et al. 1995). Natural restoration was the most-feasible, least-costly approach (Platts and Rinne 1985) and depended on in-channel and out-of-channel flows that occurred at appropriate times (Hill et al. 1991).

Pulse and base flow principles

Pulse flows in the gorge built and irrigated landforms, redistributed sediments, scoured pools, and undercut banks. Landforms such as streambanks, floodplains, terraces, and channels in the gorge were platforms on which riparian vegetation (primarily willow and cottonwood) grew. Pulse flows created vortices that placed sediments onto landforms that, with out-of-channel irrigation, set the stage for seeding and germination of riparian plants; timing of pulse flows was critical. Pulse flows had to occur when willow and cottonwood seeds were at peak maturation in the gorge; pulse flows then dispersed seeds downstream onto landforms. Higher pulse flows each spring irrigated and deposited sediments and seeds successively higher on surrounding landforms. Landforms were the key to developing the riparian vegetation that is the primary component of fish habitat in the gorge. If bare landforms in the gorge were eroded by pulse flows that were too high, platforms for riparian plants would have been lost. Therefore, we had to build and strengthen landforms to such a degree that they could withstand increasingly higher pulse flows without eroding.

Riparian seedlings sent roots into the hyporheic zone following germination and continued growth created structural stability on landforms. Riparian vegetation nearest the channel edge matured in time, and as stream flows increased in the gorge, near-stream vegetation died and/or eventually fell into the stream, adding valuable nutrients and woody debris that enhanced habitat complexity. Vegetation that was higher on landforms matured, creating landforms that were structurally sound and erosion-resistant.

As a consequence of cycles of pulse flows and vegetation growth, the channel became increasingly complex and resistant to erosion at higher flows.

Pulse flows were the "disturbance regime," and base flows were the "stability regime" in the Owens River Gorge. Pulse flows set the stage for changes in the gorge, and base flows maintained and improved on the physical and biological changes initiated by pulse flows. Base flows followed pulse flows during the growing season, a critical time for all biological components of the gorge ecosystem. We established a stable hydrologic regime during the growing period to achieve maximum riparian growth and reproductive potential.

The three-dimensional nature of groundwater determined the level where the water table and soil moisture would rise under landforms. Elevation of the hyporheic zone depended on soil particle size, the longitudinal dimension from upstream flow, the lateral dimension extending beyond channel boundaries, and a vertical dimension that resulted from the out-of-channel flow moving downward into the soil and groundwater. The hyporheic zone was at a higher elevation than the actual stream surface. Higher water tables created by incrementally higher base flows allowed riparian vegetation to grow and stabilize landforms at successively higher elevations.

Riparian seedlings became established in relation to a specific hyporehic zone associated with a specific base flow. A stable base flow steadied the water table level, and successful riparian vegetation growth depended on adequate soil moisture content above the water table throughout early plant growth phases (seedling, sprout, young plant).

Too high of an annual base flow in the gorge would have inundated landforms and drowned newly germinated riparian plants. Willow and cottonwood seedlings would not grow in standing water of any depth, and without developed root systems to hold them in place, landforms could not have withstood successively higher pulse flows. As a result, we did not change base flows in the gorge until vegetation had adequately secured landforms.

Determining annual pulse and base flows

How much pulse flow was too much if the objectives were to retain sediments, build landforms, and promote riparian vegetation throughout the gorge? The river was monitored during 10-day pulse flow periods as the discharge slowly increased. Sites and landforms particularly sensitive to erosion and sediment transport were the monitoring indicators. Pulse flows were allowed to rise to the level where incipient bank erosion began and/or fine sediments were transported no more than 1.5 river bends. At the point of erosion and/or excess sediment transport, we halted pulse flow rise, held the maximum flow for another day, and slowly ramped down to a preselected base flow. As restoration efforts proceeded, pulse flows were not allowed to become too far ahead of the base flow's ability to maintain new riparian vegetation.

A target base flow was selected each year before the pulse flow period. Base flows were selected to match the previous year's "set" of riparian vegetation to maintain new vegetation growth on landforms. Therefore, base flows had to maintain the hyporehic zone without inundating landforms on which riparian vegetation had been established. Annual base flow was determined as a function of the previous year's riparian growth and the number of sprouts (willow and cottonwood) and their relative positions on landforms. The previous year's pulse flow ideally set new vegetation farther from the streambank and higher on landforms. A one-year lag period existed between pulse flows that stimulated riparian seeding, and germination and measurement of sprouts. Thus, base flows were often held constant for two or more years as a guarantee that landforms had been secured by vegetation before moving to higher flows. Monitoring cross-channel transects and woody species provided the best information on sprout height, plant age structure, and distance from the water's edge.


Z. T. Hill


Z. T. Hill

Riparian habitat condition in the Owens River Gorge in 1991 (upper photo), the first year of rewatering, and in 1996 at a base flow of 26 cfs.

Microhabitat data were not used to establish pulse and base flows. Pool development may be accelerated with flows that scour and undercut streambanks, and create short-term physical habitat for brown trout. However, these high-velocity flows also could cause significant loss

of landforms that had not been secured by riparian vegetation, and in the long-term fish habitat could be reduced.

During 1991 and 1992 a base flow of 16 cfs was released into the gorge to fill depleted aquifers and stimulate vegetation growth. To avoid erosion of landforms not yet secured by vegetation, the first pulse flows were not applied until May 1993. Each year since 1993 increasingly larger pulse flows have been released in late May or early June (depending on the stage of riparian seed development) for approximately 10 days. Incremental changes in base flows usually followed larger pulse flows but depended on the extent of riparian development on landforms. After each pulse flow release, we monitored vegetation on landforms and microhabitat response (Hill et al. 1994). Analysis of monitoring data was used as an adaptive management tool to determine the magnitude of next year's pulse and base flows.

Monitoring methods

Sampling sites

We selected 30 sampling sites for annual monitoring throughout the gorge (Figure 1). Sites that allowed the entire gorge reach to be typified were selected above, between, and below power houses. The six uppermost sites (Crowley Reservoir to Upper Gorge power plant) were reference (i.e., control) sites; these sites experienced relatively steady flow conditions and were not influenced by pulse flows or incremental flow increases as were the lower test sites. Reference sites provided a measure of environmental events that may have influenced microhabitat and riparian vegetation but were not due to changes in flow regime. Sample sites 25 through 30 were excluded from analysis due to confounding effects of water level fluctuations above Pleasant Valley Reservoir. Sample site 7 also was excluded from the study because of construction activity below Upper Gorge power plant.

Riparian vegetation

Riparian habitat was monitored at each of the sampling sites using methods described by the U.S. Forest Service (1991). We identified vegetation types according to physiognomic class (i.e., aquatic, forested, shrub, herbaceous, and substrate) and named them within a physiognomic class by the dominant plants in the tree or shrub stratum and by hydric status (e.g., wet, mesic, dry) (Table 2).

Table 2 shows classification of vegetation types and plant species by physiogonomic class used to describe riparian habitat throughout the Owens River Gorge.

Physiogonomic class	Vegetation type	Representative species
Herbaceous	Marsh	*Typha latifolia* *Scirpus* spp.
Herbaceous	Wet meadow	*Carex nebrascensis* *Carex* spp. *Juncus balticus* *Agrostis* spp. *Muhlenbergi* spp.
Herbaceous	Mesic meadow	*Poa pratensis* *Carex douglasii* *Carex praegrasilis* *Argrostis* spp. *Distichlis spicata*
Shrub	Willow/ wet meadow	*Salix exigua*/wet meadow species *Salix laevigata*/ *Salix lutea*/ *Salix lasiandra*/
Shrub	Willow/ mesic meadow	*Salix exigua*/mesic meadow species *Salix laevigata*/ *Salix lutea*/ *Salix lasiandra*/
Shrub	Rose	*Rosa woodsii* *Ribes* spp. *Rhus trilobata*
Shrub	Rabbitbrush/ meadow	*Chrysothakmnus nauseosus* *Distichlis spicata*
Tree	Cottonwood/ mesic meadow	*Betula occidentalis*/mesic meadow species *Populus tremuloides* *Populus tricocarpa* *Fraxinus latifolia* *Celtis* spp.

Microhabitat

Microhabitat monitoring tracked changes in variables that influence fish, especially pools, riffles, substrate, canopy, bank conditions, and organic debris. We defined microhabitat using 19 stream variables that create site-specific habitat for fish and describe channel morphology (Table 3). Microhabitat was monitored at each gorge site with stream cross-sectional methods described by Platts et al. (1983).

Fish populations

Fish were monitored by direct underwater observation in the late summer (typically in August during the nonmigatory residence phase of brown trout). Underwater observation by snorkeling is a quick, inexpensive, and nondestructive census method that is not limited by deep, clear, nonconductive water. Several studies (e.g., Hicks and Watson 1985; Zubik and Fraley 1988; Thurow 1994) have shown snorkeling to be an unbiased census technique. Underwater methods followed those described by Thurow (1994), with electrofishing calibration using methods described by Hillman et al. (1992). In addition to snorkel surveys, we performed controlled creel surveys (Platts and Hill 1997) in the spring and fall to assess catch rates.

Table 3 describes statistics of continuous macrohabitat variables measured at reference and test sites in 1993 and 1997 in the Owens River Gorge. Probability values of the Wilcoxin Signed Rank test are given.

	Reference sites 1 through 6					Test sites 8 through 24				
	1993		1997			1993		1997		
Variable	Mean	SE	Mean	SE	P-value	Mean	SE	Mean	SE	P-value
Channel width (m)	9.13	0.66	9.15	0.71	0.312	10.45	1.03	10.66	0.99	0.002
Wetted width (m)	3.87	0.47	3.94	0.49	0.610	8.08	0.87	8.30	0.74	0.002
Riffle width (m)	0.39	0.27	0.36	0.06	0.051	1.75	0.39	0.63	0.18	0.000
Run width (m)	2.25	0.38	2.11	0.33	0.118	3.18	0.45	5.80	0.50	0.000
Pool width (m)	1.23	0.34	1.47	0.36	0.020	3.16	0.97	1.86	0.52	0.483
Boulder substrate (m)	0.90	0.27	0.97	0.28	0.070	2.08	0.30	2.66	0.29	0.000
Cobble substrate (m)	0.97	0.29	0.68	0.18	0.001	1.50	0.35	0.81	0.19	0.000
Gravel substrate (m)	0.34	0.19	0.49	0.18	0.002	0.80	0.23	1.03	0.17	0.000
Fine substrate (m)	1.66	0.49	1.80	0.47	0.129	3.67	1.03	3.78	0.76	0.001
Right bank angle (deg)	115.42	2.33	126.22	2.02	0.082	118.89	1.60	126.08	1.47	0.028
Left bank angle (deg.)	109.58	2.74	125.78	1.91	0.208	122.38	1.57	124.97	1.55	0.051
Average depth (m)	0.35	0.32	0.37	0.31	0.005	0.34	0.28	0.40	0.25	0.000
Thalweg depth (m)	0.48	0.42	0.52	0.47	0.001	0.48	0.36	0.62	0.36	0.000
Right bank vegetation overhang (m)	0.44	1.92	0.20	1.24	0.013	0.28	0.67	0.28	0.78	0.033
Left bank vegetation overhang (m)	0.25	0.88	0.24	1.27	0.168	0.43	1.46	0.46	1.50	0.517
Canopy cover (%)	13.64	1.57	13.33	1.72	0.000	25.67	1.65	26.00	1.52	0.000
Organic debris (%)	19.11	1.77	30.11	1.67	0.000	32.12	1.44	20.92	1.01	0.000
Right bank undercut (m)	0.05	0.35	0.04	0.08	0.001	0.05	0.30	0.02	0.20	0.000
Left bank undercut (m)	0.07	0.42	0.05	0.09	0.002	0.04	0.23	0.04	0.32	0.811

Riparian and channel habitat complexity

Relatively low pulse flows were used intentionally to provide seed transport, germination, and hyporheic zone recharge while minimizing scour effects such as erosion and sediment transport. The effects on microhabitat and channel features from low pulse flows and the incremental increase in base flow can be seen in Table 3. Except for canopy cover and organic debris (due to vegetation growth), reference sites did not exhibit any significant changes in microhabitat variables (Table 3). Most microhabitat features at the test sites changed significantly ($P < 0.001$) from 1993 to 1997 (Table 3). These changes were the result of a combination of some scour during pulse flows and increasing the base flow from 16 cfs in 1993 to 26 cfs in 1996. While most of the microhabitat changes were statistically significant, the magnitude of the changes were small. Microhabitat features such as pool and run width, and thalweg and average depth—all dependent on high-flow scour—exhibited significant but not dramatic change. The higher water surface level in 1996 caused a significant decrease in riffle and pool width as run width increased (Table 3).

Microhabitat is a direct measure of fish habitat conditions and geomorphological change. However, increasing fish habitat complexity from 1991 (when the gorge was a dry channel) to 1997 was due more to riparian vegetation than microhabitat or geomorphological change.

Pulse flow effects also can be seen in vegetation data. Cross-channel transect data (Table 4) for willow cottonwood and other woody plant species show that riparian vegetation growth at the test sites was better under flow management than at reference sites. The greatest increases in riparian vegetation occurred in 1994 (one year after the first pulse flow) and 1997.

The response of riparian plants to disturbances such as pulse flows in the initial recovery stage (1994 in the gorge) is typically rapid (Gecy and Wilson 1990) and is followed by less-dramatic but steady seasonal growth (McBride and Strahan 1984). In 1995 and 1996 riparian growth in the Owens River Gorge was less dramatic than in 1994 and 1997. In 1997 riparian vegetation again increased dramatically as additional landforms became vegetated with higher pulse flows. In comparison with reference sites, riparian vegetation at test sites increased each year as a consequence of pulse flows (Figure 2). Photo points also indicate an annual increase in biomass of riparian vegetation.

The effect of flow management on riparian vegetation by landform can be seen in Table 5. Streambank landforms at test sites exhibited the greatest diversity in riparian plant communities reflecting early to mid-seral stages and succession. The dominant vegetation type on streambank landforms at the test sites was 58% boulder and herbaceous boulder bar. Vegetation types on streambank landforms at the reference sites were in the late seral stages and had reached final plant succession. The dominant riparian vegetation type on reference site streambanks was willow/mesic meadow.

Vegetation types on floodplain landforms at test sites were 76% herbaceous sandbar, willow/wet meadow, and mesic meadow, respectively (Table 5). Reference site floodplains supported 73% marsh-type vegetation. While it appears that floodplains at test sites were developing diverse riparian communities, it is too early to determine whether the late seral stage will consist of mostly mesic meadow like reference sites or retain a mix of willow/wet meadow and mesic meadow.

Terrace landforms (the highest elevation landform) at test sites were more than 56% rabbit and sage brush (xeric

Table 4 lists number of woody species (cottonwood, willow, birch, rose) by life stage measured in 1994 and 1997 at reference and test sites in the Owens River Gorge. Probability values of the Wilcoxin Signed Rank test are given.

Vegetation	Reference sites 1 through 6			Test sites 8 through 24		
Life stage	1994	1997	P-value	1994	1997	P-value
Sprout	174	116	0.020	60	308	0.000
Young	243	284	0.105	152	733	0.000
Mature	163	192	0.382	108	622	0.000
Decadent	51	55	0.877	3	53	0.000
Dead	32	23	0.095	0	24	0.000

plant types), while reference site terraces were 73% willow/mesic meadow (Table 5). However, it is important to note that more than 27% of terraces at test sites supported riparian grasses and shrub willow vegetation. This is particularly important since pulse flows had not been of sufficient magnitude to inundate large areas of terrace landforms. Nevertheless, riparian vegetation was established on these highest elevation landforms, indicating that groundwater associated with base flows influenced riparian vegetation on terraces. Terraces at the reference sites also were not subject to pulse flows but were mostly vegetated with willow and mesic meadow, thus it is reasonable to expect that terraces at the test sites will at least mimic reference sites in time.

Willows quickly out-competed tules (*Scirpus* spp. and *Typha* spp.) as vegetated landforms developed. Tules on slightly submerged landforms initially slowed pulse flows and caused significant deposition of sediments, but as landform elevation exceeded adjacent water surface elevation, willows established and rapidly grew to out-compete tules. Young willow and cottonwood represented the age class at one year after a pulse flow. Growth of willows and cottonwoods was rapid in the gorge and compared favorably with, but slightly lower than growth rates at reference sites (Table 6).

By the third year of growth, willows in the gorge produced viable seeds, adding to the reproductive potential of the whole ecosystem. Cottonwoods generally require four years to reach maturity.

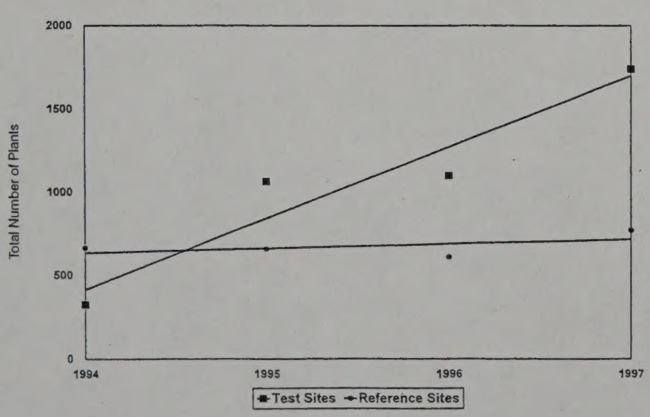

Figure 2 illustrates results of trend analysis of riparian plant (willow, cottonwood, birch, rose) numbers at Owens River Gorge reference sites 1–6 (r^2=0.56) and test sites 8–24 (r^2=0.95).

The combination of increasing pulse and base flows, the establishment and rapid growth of riparian vegetation on all landforms, and increasing microhabitat features (pools, runs, depth, and wetted width) has resulted in extremely complex habitat throughout the gorge. Small-diameter, woody limbs of willows in the water column; overhanging vegetation; deeper pools; and undercut banks all provided excellent cover for fish, and brown trout have responded to greater habitat complexity with increasing population and biomass.

Fish response

The river below the Upper Gorge power plant was stocked with approximately 30,000 brown trout in 1994. Some rainbow trout (*Oncorhynchus mykiss*), Owens sucker (*Catostomus fumelventris*), speckled dace, and Owens tui chub occur in the gorge, but the dominant fish species is brown trout.

Snorkel surveys performed in 1995, 1996, and 1997 correlated well with electrofishing (r values of 0.74 to 0.85, $P < 0.05$). Brown trout numbers have increased each year since stocking (Figure 3), which indicates that, so far, spawning and recruitment is not limiting, and annual mortality is low. A healthy fishery in good condition has quickly developed in response to restoration efforts.

Electrofishing data from three sites were used to estimate annual brown trout populations (Van Deventer and Platts 1989). The brown trout population in the gorge increased by approximately 40% from an estimated population of 1,815 trout/mile in 1996 to almost 3,000 trout/mile in 1997. Creel survey results indicated catch rates increased from 0 fish/hr in 1991 to between 5.8 and 7.1 fish/hr (with a maximum catch rate of 15.7 fish/hr) in 1996.

Brown trout were able to spawn and maintain healthy size structure (Figure 3), which indicates that fish habitat criteria for different life stages were met. Limiting conditions (spawning, rearing, food competition, predation, etc.) are hypothesized to be eased as a function of habitat response to each incremental increase in pulse and base flows. As flows increased, more spawning, rearing, and escapement habitat was created; riverine-riparian habitat complexity increased; and the food base expanded proportionally. Brown trout distribution throughout the gorge (Figure 5) followed changes in habitat complexity. Riparian habitat, channel configuration, and microhabitat conditions became increasingly complex from upstream to downstream. Brown trout distribution followed this trend, exhibiting increasing numbers of trout that used the increasingly complex and diverse downstream habitat.

A river ecosystem restored from a dysfunctional to functional state may or may not produce a large number of big fish. Every stream has a unique carrying capacity with natural limitations inherent in its functional state that dictate fish numbers and size. Depending on the

restoration goal, fishery success can be measured in many ways. Success may be a blue-ribbon trout fishery, a self-sustaining population with adequate recruitment, growth and age distribution, and low mortality rates, or a healthy population with high endemic species biodiversity. However, fishery success may not be the functional endpoint of restoration. Kauffman et al. (1997) state that because an entire suite of organisms, physical features, and processes comprise an ecosystem, a species-only or single-process approach to restoration will likely fail.

Restoration endpoint

Restoration of the Owens River Gorge is an ongoing process, but managers must begin focusing on how to identify the endpoint and final flow regime necessary to sustain the gorge ecosystem. Common endpoints used in assessing the recovery of river systems are divided into either biotic or abiotic resources.

Milner (1994) describes structural and functional endpoints for biotic resources and habitat and water quality endpoints for abiotic resources. *Structural endpoints* cover community assemblages with such attributes as density, number of species, species diversity, etc., and typically involve comparison with the predisturbance condition or a reference community. *Functional endpoints* refer to the functioning of the community (for example, species equilibrium) and may be evaluated independently of a reference community. An ecosystem, however, is generally regarded as a synergistic unit that comprises both biotic and abiotic resources, thus it is impossible to consider a community in isolation from the environment in which it exists.

Table 5 shows riparian vegetation types and percent of total vegetated area measured on landforms at test and reference sites in 1997 in the Owens River Gorge.

Vegetation type	Description	Landforms in Test Sites 8–24				Landforms in reference sites 1–6			
		Stream-bank	Flood-plain	Terrrace	Island	Stream-bank	Flood-plain	Terrace	Island
Streambar									
Silt-muck bar	Dominant substate silt-muck	0	0	0	0	0	0	0	0
Herbaceous siltbar	>30% vegetation cover	0	0	0	0	0	0	0	0
Sandbar	Dominant substrate sand	0.3	3.5	0	0	0	0	0	0
herbaceous sandbar	>30% vegetation cover	8.5	35.6	8	56	0	0	0	0
Gravelbar	Dominant substrate gravel (<2")	1.1	0	0.5	0	0	0	0	0
Herbaceous gravelbar	>30% vegetation cover	1.5	0	0	0	0	0	0	0
Cobblebar	Dominant substrate cobble (2"–12")	0.7	0	0.2	0	0	0	0	0
Herbacous cobblebar	>30% vegetation cover	1.5	0	0.4	0	1.5	0	0	0
Boulderbar	Dominant substrate boulder (>12")	31.8	0	1.7	14	5	0	0	0
Herbaceous boulderbar	>30% vegetation cover	26.1	9.1	5.2	14	16.2	0	0	0
Eroded bank	Eroding streambank	0	0	0	0	0	0	0	0
Herbaceous									
Marsh	Bullrush, cattail, reed grass	0	2.9	0	0	0	72.7	0	0
Wet meadow	Sedges	0.3	3.1	0	0	0.5	5	1.6	100
Mesic meadow	Riparian grasses	1.3	18.9	13.7	0	4.2	6.1	0.6	0
Riparian shrub									
Willow/wet meadow	Willow with sedges	0.2	21.6	0	0	0.4	3.8	0	0
Tree willow/wet meadow	Willow with ruoarua grasses/forbes	0	0	0	0	0	0	0	0
Tamarisk/wet meadow	Tamarisk with sedges	0	0	0	0	0	0	0	0
Willow/mesic meadow	Shrub willow with riparian grasses/forbs	9.8	5.1	13.7	6	45.9	8.7	73.6	0
Tree willow/mesic meadow	Trunky willow	0	0	0	0	0	0	0	0
Tamarisk/mesic meadow	Tamarisk with other non-willow shrubs	0.2	0	0	0	14.1	3.5	7.4	0
Rose	Rose with other (non-willow) shrubs	0.2	0	0	0	14.1	3.5	7.4	0
Upland shrub									
Rabbit brush/sage	Terrestrial brush/sage	16.6	0	56.5	0	12.3	0	16.7	0
Riparian tree									
Cottonwood/mesic meadow		0	0	0	0	0	0	0	0

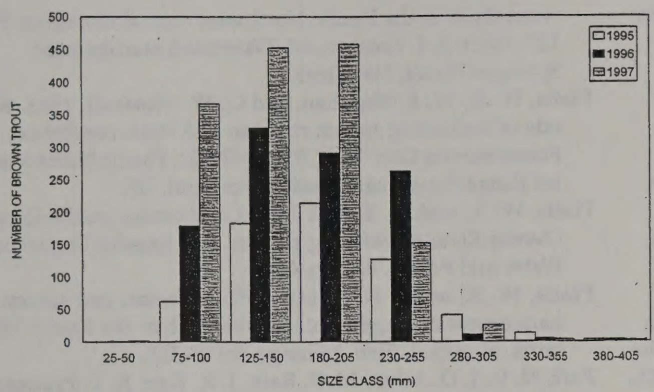

Figure 3 shows length-frequency distribution of brown trout from 1995 to 1997 snorkel surveys in even numbered test sites in the Owens River Gorge.

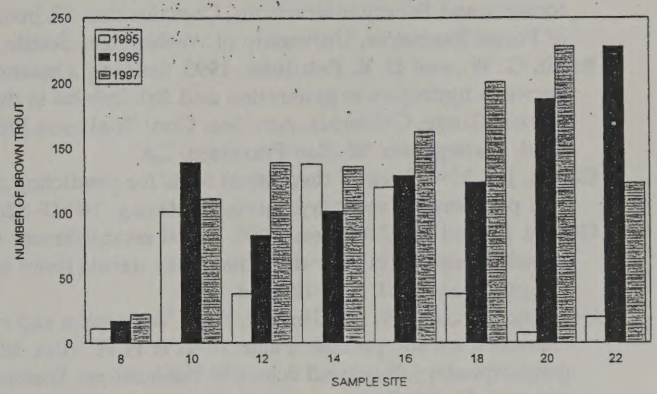

Figure 4 reports distribution of brown trout by sample site from 1995 to 1997 snorkel surveys in even-numbered test sites in the Owens River Gorge.

A critical question regarding restoration endpoint is whether the structural and functional endpoints of a recovered community can be maintained without constant management. Cairns (1990) argued that unless a self-sustaining community based on natural reproduction, succession, and adaptation is attained, system restoration has not been achieved.

Experience gained from the Owens River Gorge restoration effort shows there are several possible endpoints. The gorge ecosystem can be made functional at many different flow levels, depending on the degree to which vacant landforms are vegetated with pulse flows and maintained with base flows. At a given flow regime, riparian habitat, in-channel habitat, stream morphology, and brown trout populations will eventually reach an asymptote. Biotic and abiotic resources will tend toward steady conditions that fluctuate around predictable means; eventually the ecosystem will become a self-sustaining community based on natural reproduction, succession, and adaptation. This level of restoration may be different from historical conditions and may be far below the ecosystem's maximum potential. It is apparent that careful identification of goals, with measurable and achievable endpoints, must be the first step in restoration planning.

Conclusions

After five years of natural restoration, the Owens River Gorge ecosystem has made a rapid comeback to a functional ecosystem capable of sustaining a productive fishery and riparian biota. The river ecosystem has responded so well to incremental base and pulse flows that it has been possible to implement pulse flows twice as high as originally planned (Table 1). On the other hand, to provide adequate growing time for riparian vegetation and to secure landforms, base flows have not been increased as rapidly as originally planned (Table 1).

The key to ecosystem recovery and sustainable biota in the gorge is a multiple-flow regime that allows nature to build and maintain riparian habitat. Monitoring results in the Owens River Gorge validate the approach used: incrementally restoring a riverine-riparian structure for the river to "hold on to" at high flows. We are meeting our original restoration goal by retaining sediments that annually build streambanks and vegetation near the water's edge.

Table 6 illustrates average annual maximum and minimum growth of young age-class willow and cottonwood vegetation at reference and test sites in the Owens River Gorge, 1993–1997.

Year	Test sites 8–24		Reference sites 1–6	
	Minimum Growth (m)	Maximum Growth (m)	Minimum Growth (m)	Maximum Growth (m)
1993	0.7	1.5	0	1.6
1994	0.9	1.5	0.5	1.3
1995	0.6	1.8	0.5	1.4
1996	0.5	1.9	0.5	1.6
1997	0.5	1.8	0.7	1.5

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The "Mixer," a Colorado pikeminnow spawning area in the San Juan River

Flow Recommendations for the San Juan River

May 1999

Prepared by:
The San Juan River Basin
Recovery Implementation Program
BIOLOGY COMMITTEE

Compiled and Edited by:
PAUL B. HOLDEN

PREFACE

This report was prepared by the Biology Committee of the San Juan River Basin Recovery Implementation Program (SJRIP) and is based on all data available at the time it was prepared. Some field collections from 1997 and early 1998 had not been fully analyzed and, therefore, were not included in the report. Information collected on the San Juan River during the 7-year research period that is not pertinent to flow recommendations is also not included. Final research reports and a Synthesis Report that will compile and synthesize information on other aspects of recovery of the endangered fish in the San Juan River are scheduled to be completed in 1999.

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EXECUTIVE SUMMARY

INTRODUCTION

This report presents the results of a process to develop flow recommendations for the native fish community, including the endangered Colorado pikeminnow (*Ptychocheilus lucius*) and razorback sucker (*Xyrauchen texanus*), in the San Juan River of New Mexico, Colorado, and Utah. Flow recommendations are a major milestone of the San Juan River Basin Recovery Implementation Program (SJRIP), which was initiated in 1992 with the following two goals:

1. To conserve populations of Colorado squawfish and razorback sucker in the basin, consistent with the recovery goals established under the Endangered Species Act, 16 U.S.C. 1531 et seq.

2. To proceed with water development in the basin in compliance with federal and state laws, interstate compacts, Supreme Court decrees, and federal trust responsibilities to the Southern Utes, Ute Mountain Utes, Jicarillas, and the Navajos.

Mimicry of the natural hydrograph is the foundation of the flow recommendation process for the San Juan River. Scientists have recently recognized that temporal (intra- and interannual) flow variability is necessary to create and maintain habitat and to maintain a healthy biological community in the long term. Restoring a more-natural hydrograph by mimicking the variability in flow that existed before human intervention provides the best conditions to protect natural biological variability and health. The linkages between hydrology, geomorphology, habitat, and biology were used to define mimicry in terms of flow magnitude, duration, and frequency for the runoff and base-flow periods. The flow characteristics of these linkages were compared with the statistics of the pre-Navajo Dam hydrology to assist in fine-tuning the flow recommendations. The flow recommendations require mimicry of statistical parameters of flow, based on the linkages developed and the statistical variability of the pre-dam hydrology rather than mimicry of each annual hydrograph. A 65-year-long period of record (1929 to 1993) was used to assess the relationship between water development scenarios and the ability to meet the flow recommendations.

Data were gathered and analyzed during a 7-year research period (1991 to 1997) to determine fish population and habitat responses to reregulation of Navajo Dam to mimic a natural hydrograph. The research involved quantification of several relationships, including flow/geomorphology, geomorphology/fish habitat, and flow/habitat availability relationships.

The SJRIP will use an adaptive management process, along with monitoring and continued research, to adjust the flow recommendations in the future. The ability to adaptively manage the system is

important because flow recommendations can be refined in response to the emerging understanding of the mechanisms involved in recovery of the endangered species in the San Juan River.

This report is one of two reports that address the results of the 7-year research program. This report focuses on the analysis and integration of biological, hydrologic, and geomorphological data to determine flow needs of the endangered fish species. A companion report, to be produced in 1999, will compile and synthesize information on other aspects of recovery of the endangered fishes in the San Juan River. The companion report will specifically address issues such as contaminants, propagation, nonnative species control, and fish-passage needs.

RESULTS OF THE 7-YEAR RESEARCH PERIOD

The San Juan River is similar to other Upper Colorado River Basin (Upper Basin) streams, primarily the Green and Colorado rivers, in that they are all large rivers with high spring flows and low base flows, they are all fairly turbid most of the time, they typically have sand and cobble substrate, and they are all subject to late summer and fall thunderstorm activity. The San Juan River is also similar to other portions of the Upper Basin in that it once supported populations of Colorado pikeminnow and razorback sucker that have declined after the completion of major dams. However, the San Juan River is different than the Green and Colorado rivers primarily because it has a steeper overall slope, a higher overall sediment concentration, and more late summer and fall flood events. No wild razorback sucker were found in the San Juan River during the research period, and the Colorado pikeminnow population appears to be smaller than 100 individuals. Navajo Dam began affecting flows in the San Juan River in 1962, and post-dam flows had lower spring flows and higher late summer, fall, and winter flows than occurred during pre-dam periods. The advent of research flows in 1992 to 1997 produced flows more typical of the pre-dam era.

Habitat needs of the two endangered fishes in the San Juan River involve a complex mix of low-velocity habitats such as eddies, pools, and backwaters adjacent to swifter run and riffle habitats. Habitat use changes with time of year and activity (e.g., spawning, feeding, nursery areas). A natural hydrograph, in terms of peak spring flows and late summer base flows, is important to not only provide the proper habitats at the correct time, but also to provide natural temperatures and productivity cycles for those habitats.

Two key habitats important to Colorado pikeminnow and other native species that were used extensively in the flow recommendation process were cobble bars and backwaters. Cobble bars are spawning areas for Colorado pikeminnow, and the fish appear to have fidelity for a certain area of the San Juan River called "the Mixer" for spawning. In the Green River, similar fidelity to spawning areas is seen for both Colorado pikeminnow and razorback sucker. An important feature of Colorado pikeminnow spawning bars is that the cobbles are very clean with relatively little fine sediments between individual cobbles. Clean cobble bars are more rare in the San Juan River, as well as in other Upper Basin rivers, than just a typical cobble bar.

Backwaters are an important habitat for young native fishes, including Colorado pikeminnow. During studies of young stocked Colorado pikeminnow in the San Juan River, the fish were found in backwaters 60% of the time, but they were found in other low-velocity habitats (e.g. pools, pocket water) nearly 40% of the time. In the Green River, young Colorado pikeminnow are found in backwaters more often than fish in the San Juan River, and studies have shown that the San Juan River has relatively small amounts of backwaters compared with the Green and Colorado rivers. But the success of the stocked Colorado pikeminnow in the San Juan River has shown that this system has the habitats necessary for the survival and growth of these young fish.

Studies assessing the flows needed to build and maintain cobble bars and backwaters similar to those used by Colorado pikeminnow were an important part of the 7-year research effort. These studies showed that relatively high flows were needed to build and clean these habitats, but that lower flows were needed to make them more abundant at the proper time of the year.

During the 7-year research period, a number of responses to the reregulation of Navajo Dam were identified in the native fish community. Colorado pikeminnow young were found in very low numbers, or not at all, during low spring runoff years, and in larger numbers during higher flow years. The young of bluehead sucker and speckled dace, two other native species, were found in greater numbers during high flow years compared with low flow years. Flannelmouth sucker, another native species, tended to decline during the research period, but still remained the most abundant native species in the river. The change to a more-natural hydrograph during the research period resulted in more cobble and less sand habitats in the river, apparently favoring bluehead sucker and speckled dace rather than flannelmouth sucker.

Nonnative fishes in the San Juan River are potential predators and competitors with the native species and have been implicated in the decline of the native fishes throughout the Colorado River Basin. Populations of some nonnative fishes changed during the research period, but no major reduction in nonnative fish numbers were documented. Some authors have suggested that nonnative fishes may be reduced by high natural flows, but this was not the case in the San Juan River during the 7-year research period. Contaminants were also studied as a potential limiting factor for native fishes, but no pattern of contaminant concentrations and flow was found. Table S.1 summarizes the biological and habitat responses that were found during the research period and the flows that were important in producing those responses.

FLOW RECOMMENDATION

RiverWare, a generic hydrologic model, was used as the primary modeling tool for developing the flow recommendations. The model simulates the flow in the river at various gages at different points in time, including the past, present, and future. It does this by incorporating all past, present, and potentially future water development projects into the model. The 1929 to 1993 period of record was used in the model to simulate flows under the various development scenarios. Existing gaging stations were used to calibrate the model to ensure it was working properly for historic conditions.

Table S.1. Flow requirements needed to produce important biological responses and habitats in the San Juan River.

BIOLOGICAL RESPONSE/ HABITAT REQUIREMENT	FLOW CHARACTERISTIC
Reproductive success of Colorado pikeminnow lower in years with low spring runoff peaks, and higher in years with high and broad runoff peaks.	Mimicry of a natural hydrograph, especially during relatively high runoff years.
Decline in flannelmouth sucker abundance, increase in bluehead sucker abundance, and increased condition factor in both species.	Mimicry of natural hydrograph with higher spring flows and lower base flows.
Bluehead sucker reproductive success.	Increased number of days of spring runoff >5,000 and 8,000 cfs correlated with increased success.
Speckled dace reproductive success.	Increased number of days of spring runoff >5,000 and 8,000 cfs correlated with increased success.
Success of stocking YOY Colorado pikeminnow and subadult razorback sucker.	Mimicry of natural hydrograph has provided suitable habitat for these size-classes.
Eddies, pools, edge pools, other low-velocity habitats year round for adult Colorado pikeminnow and razorback sucker.	Mimicry of natural hydrograph has lowered base flows to provide more low-velocity habitats. Flows >10,000 cfs provide more channel complexity which provides for more habitat complexity.
Flows to cue razorback sucker and Colorado pikeminnow for migration and/or spawning.	Mimicry of natural hydrograph with higher spring flows.
Adult Colorado pikeminnow and razorback sucker use complex river areas.	Flows >10,000 cfs provide more channel complexity which provides for more habitat complexity, lower base flows add to amount of low-velocity habitats.
Clean cobble bars for spawning of all native species, especially Colorado pikeminnow.	Flows >8,000 cfs for 8 days to construct cobble bars, and >2,500 cfs for 10 days to clean cobble bars, during spring runoff.
Backwaters and other low-velocity habitats are important nursery habitats for Colorado pikeminnow and other native fishes.	High spring flows create conditions for backwater formation, low base flows allow them to appear in late summer and fall, flows >5,000 cfs for 3 weeks create and clean backwaters.
Flooded bottomlands appear to be important nursery areas for razorback sucker, but other habitats may be used in the San Juan River.	Overbank flows (> 8,000 cfs) increase flooded vegetation, and backwaters formed in association with edge features maximize on receding flows of 8,000 to 4,000 cfs.
Temperatures of 10 to 14 °C at peak runoff for razorback sucker spawning and near 18 to 20 °C at bottom of descending limb for Colorado pikeminnow spawning.	Proposed releases from Navajo Dam are too cool to replicate pre-dam temperature timing, but temperatures are above spawning threshold for Colorado pikeminnow during the correct period.
Reduction of nonnative fish abundance.	Most nonnative fishes did not decrease during research period, summer flow spikes reduce numbers of red shiner in secondary channels in the short term.

Note: cfs = cubic feet per second, YOY = young-of-the-year.

The model was completed with input from the Bureau of Reclamation, Bureau of Indian Affairs, and the states of New Mexico and Colorado.

Mimicry of the natural hydrograph is the foundation of the flow recommendation process for the San Juan River. The flow recommendations require mimicry of statistical parameters of flow based on flow/geomorphology/habitat linkages and the statistical variability of the pre-dam hydrology rather than mimicry of each annual hydrograph. Therefore, the resulting flows will not mimic a natural hydrograph in all years, but will mimic the variation and dynamic nature of the 65-year record of the San Juan River.

The hydrograph recommendations are designed to meet the conditions required to develop and maintain habitat for Colorado pikeminnow and razorback sucker and provide the necessary hydrologic conditions for the various life stages of the endangered and other native fishes. The conditions are listed in terms of flow magnitude, duration, and frequency during the spring runoff period. Duration is determined as the number of days that the specified flow magnitude is equaled or exceeded during the spring runoff period of March 1 to July 31. Frequency is the average recurrence of the conditions specified (magnitude and duration), expressed as a percent of the 65 years of record analyzed (1929 to 1993). The underlying assumption in the flow conditions is that, over a long period of time, history will repeat itself: if the conditions were met during the past 65 years, they will also be met in the future. To the extent that the water supply is different in the future, then the natural condition would also be altered and the conditions of mimicry would be maintained, although the exact flow recommendation statistics may not be met.

To allow for gage and modeling error and the difference between the flows at the historical gage at Bluff, Utah, and the Four Corners gage, maximum allowable durations are computed for 97% of the target flow rate. In most cases, the primary recommendation is for a specified flow rate (i.e., 10,000 cubic feet per second (cfs)) of a minimum duration (i.e., 5 days) for a specific frequency of occurrence (i.e., 20% of the years). In addition to the primary recommendation, variability in duration is desirable to mimic a natural hydrograph. Therefore, a frequency table for a range of durations for each flow rate is recommended. A maximum duration between occurrences is also specified to avoid long periods when conditions are not met, since such long periods could be detrimental to the recovery of the species. The maximum period without reaching a specified condition was determined as twice the average required interval (except for the 80% recurrence of the 2,500 cfs condition, where 2 years is used). For example, if the average interval is 1 year in 3, then the maximum period between meeting conditions would be 6 years. The maximum periods were based on the collective judgement of Biology Committee members after review of historical pre-dam statistics. Following are the conditions specified:

A. Category: Flows > 10,000 cfs during runoff period (March 1 to July 31).

Duration: **A minimum of 5 days between March 1 and July 31.**

Frequency: **Flows > 10,000 cfs for 5 days or more need to occur in 20% of the years on average for the period of record 1929-1993.** Maximum number of consecutive years without meeting at least a flow of 9,700 cfs (97% of 10,000 cfs) within the 65-year period of record is 10 years.

Purpose: Flows above 10,000 cfs provide significant out-of-bank flow, generate new cobble sources, change channel configuration providing for channel diversity, and provide nutrient loading to the system, thus improving habitat productivity. Such flows provide material to develop spawning habitat and maintain channel diversity and habitat complexity necessary for all life stages of the endangered fishes. The frequency and duration are based on mimicry of the natural hydrograph, which is important for Colorado pikeminnow reproductive success and maintenance of channel complexity, as evidenced by the increase in the number of islands following high flow conditions. Channel complexity is important to both Colorado pikeminnow and razorback sucker.

B. Category: Flow > 8,000 cfs during runoff period.

Duration: **A minimum of 10 days between March 1 and July 31.**

Frequency: **Flows > 8,000 cfs for 10 days or more need to occur in 33% of the years on average for the period of record 1929-1993.** Maximum number of consecutive years without meeting at least a flow of 7,760 cfs (97% of 8,000 cfs) within the 65-year period of record is 6 years.

Purpose: Bankfull discharge is generally between 7,000 and 10,500 cfs in the San Juan River below Farmington, New Mexico, with 8,000 cfs being representative of the bulk of the river. Bankfull discharge approximately 1 year in 3 on average is necessary to maintain channel cross-section. Flows at this level provide sufficient stream energy to move cobble and build cobble bars necessary for spawning Colorado pikeminnow. Duration of 8 days at this frequency is adequate for channel and spawning bar maintenance. However, research shows a positive response of bluehead sucker and speckled dace abundance with increasing duration of flows above 8,000 cfs from 0 to 19 days. Therefore, the minimum duration was increased from 8 to 10 days to account for this measured response. Flows above 8,000 cfs may be important for providing habitat for larval razorback sucker if flooded vegetation and other habitats formed during peak and receding flows are used by the species. This flow level also maintains mimicry of the natural hydrograph during higher flow years, an important feature for Colorado pikeminnow reproductive success.

Category: Flow > 5,000 cfs during runoff period.

Duration: **A minimum of 21 days between March 1 and July 31.**

Frequency: **Flows > 5,000 cfs for 21 days or more need to occur in 50% of the years on average for the period of record 1929-1993.** Maximum number of consecutive years without meeting at least a flow of 4,850 cfs (97% of 5,000 cfs) within the 65-year period of record is 4 years.

Purpose: Flows of 5,000 cfs or greater for 21 days are necessary to clean backwaters and maintain low-velocity habitat in secondary channels in Reach 3, thereby maximizing nursery habitat for the system. The required frequency of these flows is dependent upon perturbating storm events in the previous period, requiring flushing in about 50% of the years on average. Backwaters in the upper portion of the nursery habitat range clean with less flow but may be too close to spawning sites for full utilization. Maintenance of Reach 3 is deemed critical at this time because of its location relative to the Colorado pikeminnow spawning area (RM 132) and its backwater habitat abundance.

3. Category: Flow >2,500 cfs during runoff period.

Duration: **A minimum of 10 days between March 1 and July 31.**

Frequency: **Flows > 2,500 cfs for 10 days or more need to occur in 80% of the years on average for the period of record 1929-1993.** Maximum number of consecutive years without meeting at least a flow of 2,425 cfs (97% of 2,500 cfs) within the 65-year period of record is 2 years.

Purpose: Flows above 2,500 cfs cause cobble movement in higher gradient areas on spawning bars. Flows above 2,500 cfs for 10 days provide sufficient movement to produce clean cobble for spawning. These conditions also provide sufficient peak flow to trigger spawning in Colorado pikeminnow. The frequency specified represents a need for frequent spawning conditions but recognizes that it is better to provide water for larger flow events than to force a release of this magnitude each year. The specified frequency represents these tradeoffs.

E. Category: Timing of the peak flows noted in A through D above must be similar to historical conditions, and the variability in timing of the peak flows that occurred historically must also be mimicked.

Timing: Mean date of peak flow in the habitat range (RM180 and below) for any future level of development when modeled for the period of 1929 to 1993

must be within 5 days ± of historical mean date of May 31 for the same period.

Variability: Standard deviation of date of peak to be 12 to 25 days from the mean date of May 31.

Purpose: Maintaining similar peak timing will provide ascending and descending hydrograph limbs timed similarly to the historical conditions that are suspected important for spawning of the endangered fishes.

F. Category: Target Base Flow (mean weekly nonspring runoff flow).

Level: 500 cfs from Farmington to Lake Powell, with 250 cfs minimum from Navajo Dam.

Purpose: Maintaining low, stable base flows enhances nursery habitat conditions. Flows between 500 and 1,000 cfs optimize backwater habitat. Selecting flows at the low end of the range increases the availability of water for development and spring releases. It also provides capacity for storm flows to increase flows and still maintain optimum backwater area. This level of flow balances provision of near-maximum low-velocity habitat and near-optimum flows in secondary channels, while allowing water availability to maintain the required frequency, magnitude, and duration of peak flows important for Colorado pikeminnow reproductive success.

G. Category: Flood Control Releases (incorporated in operating rule).

Control: Handle flood control releases as a spike (high magnitude, short duration) and release when flood control rules require, except that the release shall not occur earlier than September 1. If an earlier release is required, extend the duration of the peak of the release hydrograph. A ramp up and ramp down of 1,000 cfs per day should be used to a maximum release of 5,000 cfs. If the volume of water to release is less than that required to reach 5,000 cfs, adjust the magnitude of the peak accordingly, maintaining the ramp rates. Multiple releases may be made each year. These spike releases shall be used in place of adjustments to base flow.

Purpose: Historically, flood control releases were made by increasing fall and winter base flows. This elevates flows above the optimum range for nursery habitat. Periodic clean-water spike flows improve low-velocity habitat quality by flushing sediment and may suppress red shiner and fathead minnow abundance.

Operating rules for Navajo Dam were developed in cooperation with the Bureau of Reclamation to demonstrate how the dam may be operated to meet the flow recommendations. These suggested rules determine the timing and size of release flows to maximize the ability of the river to meet the flow recommendations. Releases to produce a peak spring flow are not made every year because saving water, (1) for human use, and (2) to make a larger peak in a future year, is incorporated into the rules. The flow recommendations, and use of the operating rules, will provide flows in the San Juan River that will promote the recovery of the two endangered fish species. As presently configured, the flow recommendations may also allow for a significant amount of future water development in the basin.

This report addresses the science of the development of flow recommendations for the San Juan River. It does not address the impact of the recommended flows on the holders of water rights in the San Juan River Basin. Legal and management factors to be considered by the U.S. Fish and Wildlife Service and affected parties will determine which holders of water rights will be affected by these flow recommendations. The SJRIP recognizes that the flow criteria and operating rules discussed herein are only recommendations that are subject to further refinement through the SJRIP adaptive management process and pursuant to the National Environmental Policy Act.

STREAM SYSTEMS TECHNOLOGY CENTER

STREAM NOTES

To Aid in Securing Favorable Conditions of Water Flows

October 1995

Artificial Stream Restoration
Money Well Spent Or An Expensive Failure?[1]

INTRODUCTION

Although artificial stream restoration for improved fish/trout habitat has been in vogue for at least a century, these endeavors have been insufficiently studied, and failures and successes inadequately documented (Hall and Baker 1982, Platts and Rinne 1985, Platts and Nelson 1985, Beschta and Platts 1986, Elmore and Kauffman 1994). The lack of data has occurred at a time when native fish populations are declining and political pressures (e.g., Endangered Species Act, Pacific Northwest salmon issues) are increasing to provide additional sources of money for restoring damaged streams and preventing the extirpation of species. Although the Bonneville Power Administration (BPA), the US Forest Service (USFS), the Bureau of Land Management (BLM), and the Pacific Northwest States are spending millions of dollars annually for the improvement of salmonid habitat, this financial effort may not be providing the desired benefits.

To obtain scientific, economic, and social evaluation of the various types of stream alteration projects are absolutely needed to guide future decisions.[2] However, such information gaps exist because the scientific community has not evaluated the ecological effects of various types of restoration projects. In addition, economic evaluations of the benefits resulting from project structures of stream [illegible] have received little attention (Everest and Rodgers 1982). Although the research necessary to implement successful rehabilitation of riparian-stream environments is in its infancy, Beschta et al. (1991) have alerted the fisheries profession and other natural resource managers that estimates of cost-effectiveness and total biological benefits are needed to help set priorities for future habitat alteration projects.[3] Furthermore, it is possible that many previous "restoration" or "enhancement" projects have actually resulted in further degradation of the ecological functions of streams (e.g., Frissell et al. 1992, Kauffman et al. 1993).

[1] This article contains portions of a paper originally presented at the 1994 Universities Council on Water Resources Symposium "Environmental Restoration."

The authors are: Robert L. Beschta, Hydrologist and Professor at Oregon State University in Corvallis, Oregon; William S. Platts, Fisheries Scientist with Ecosystem Sciences in Boise, Idaho; J. Boone Kauffman, Riparian Ecologist and Associate Professor at Oregon State University; and Mark T. Hill, Fisheries Biologist with Ecosystem Sciences. Excerpts from their paper appear with permission.

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Credible scientific, economic, and social evaluation of the various types of stream alteration projects are critically needed to guide future decisions. However, major information gaps exist because the scientific community has not evaluated the ecological effects of various types of restoration projects. In addition, economic evaluations of the benefits resulting from project costs are of critical importance yet have received little attention (Reeves and Roelofs 1982). Although the research necessary to implement successful rehabilitation of riparian-stream environments is in its infancy, Everest et al. (1991) have alerted the fisheries profession and other natural resources managers that estimates of cost-effectiveness and total biological benefits are needed to help set priorities for future habitat alteration projects. Furthermore, it is possible that many previous "restoration" or "enhancement" projects have actually resulted in further degradation of the ecological functions of streams (e.g., Beschta et al. 1992, Kauffman et al. 1993).

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IN THIS ISSUE

In this paper, we discuss the historic and present status of stream restoration in the western United States. Most of these projects were undertaken with the express purpose of improving or enhancing fisheries habitat. Case histories with a sufficient data base or study intensity to develop a better understanding of their effects are reviewed although detailed statistical evacuations are not included. Our objective is to provide improved insights to project decision makers for reevaluating whether expenditures have achieved desired results.

HISTORICAL SETTING

During most of this century, the desire to provide sport fishing opportunities through artificial stream restoration experienced a series of fits and starts (Hunter 1991). By the 1930's, professionals and lay people were deep in modifying streams and their banks. H.S. Davis, Chief of the U.S. Bureau of Fisheries, commented in the 1930s that "...hardly a foot of stream has been left in its original condition... Of what benefit to a stream is it to construct cover (artificial) for many times the number of fish the stream (food resources) can support?" Seventy years ago, biologists were pointing out that money and time spent does not equal products received (Hunter 1991). Those critics, were largely ignored by the fisheries profession as evidenced by the large stream repair projects that followed over the next 70 years. Because only a small fraction of the tools and ecological knowledge of stream systems known today was at their disposal, it's understandable why fisheries specialists in the 1930s were enthralled by the concept that people could construct a better stream. They believed they were breaking new ground (Hunter 1991). However, given our current knowledge-base, it is ironic that many fisheries biologists and other natural resources specialists continue to subscribe to the idea that the physical alteration of a stream provides a simple mechanism for improved or restored habitat conditions.

"...given our current knowledge-base, it is ironic that many fisheries biologists and other natural resources specialists continue to subscribe to the idea that the physical alteration of a stream provides a simple mechanism for improved or restored habitat conditions."

In 1952 the US Forest Service published its first major handbook on improving stream habitat (USDA Forest Service 1952). A second major handbook followed in 1985 (Seehorn 1995). This cook-book approach to habitat management admitted that many mistakes had happened in the past but it also concluded that much has been learned (Hunter 1991). The manual, however, did not dwell on what those past mistakes were or what had been learned. In 1992, the USFS published its latest Stream Habitat Improvement Handbook (Seehorn 1992) which superseded the 1985 version. The 1992 handbook provided an excellent primer on how to be a "water carpenter." However, the manual did not expand on anything learned from past modes of operation and there was nothing in the manual regarding the effectiveness of past projects or benefit cost ratios to be expected. The manual identified a large number of instream projects but little understanding or background on whether these proposed practices actually provided any benefits or how to consider proposed habitat alterations within the ecologic and geomorphic context of a particular stream reach or watershed. Similar comments apply to a stream rehabilitation manual presented by House et al. (1988).

White and Brynildson (1967) moved the understanding of stream restoration forward with their 1967 trout management manual. Perhaps their most important conclusion was "if a stream is already in good shape leave it alone." They emphasized that remaining unspoiled waters were highly valuable, and the main stream management effort today was to guarantee their preservation for the future. White and Brynildson (1967) were one of the first to emphasize that vegetation should be managed first before implanting hard structures such as dams, deflectors, and rip-rap.

HABITAT MODIFICATION IN AN ECOLOGICAL SETTING

The desire to artificially alter instream fish habitat has resulted from a variety of reasons. In many instances, stream habitat degradation has proceeded to the point where one or more limiting factors, such as high water temperatures, excess fine sediment, lack of pools, insufficient cover, limited allochthonous inputs have contributed to declines in fish populations. Once limiting factors have been delineated, an in-channel habitat alteration project is often developed. Such alterations have occurred even if the limiting factors are unrelated to inchannel problems (i.e., the loss of cover and streambank stability due to livestock grazing, logging, agricultural practices, etc.). The focus of these projects is usually directed toward **in-channel alterations** for a variety of reasons including:

- An inadequate understanding of riparian/stream ecosystems (e.g., many stream biologists may not understand the ecological functions of streamside vegetation or the natural disturbance patterns that shape both channels and an array of habitat features)
- Political purposes (e.g., it is socially or politically unacceptable to change ongoing land use practices that are causing degradation)
- Limitations of project funding (e.g., the available money can only be spent on instream habitat features and not on improving stewardship of riparian systems)
- Management styles that emphasize quantifiable project results (e.g., building a specific number of structures during the fiscal year can have a much higher priority for many resource managers than improved stewardship decisions)
- A focus on structure and not process (e.g., blindly accepting the concept that one can never add too much large woody debris to a stream while totally ignoring those factors limiting or reducing the natural recruitment of large wood debris)
- The desire to create a better system than can occur naturally by simplistic alteration of a specific habitat feature (e.g., adding large wood, boulders, spawning gravels in areas where non naturally exist)
- A belief based on an inadequate understanding of the complexity of riparian/stream interactions that structures can mitigate for management practices that degrade riparian/aquatic habitats (e.g., structures are installed while allowing the continuation of abusive grazing, logging, or other land use practices)
- Land ownership (e.g., while water and fish are usually considered public resources, the land on either side of the channel may be in private ownership and thus the permission and cooperation of landowners is required for out-of-channel restoration efforts)
- A reductionist perspective of how to manage stream ecosystems (e.g., altering the in-channel environment can be perceived as a simplistic cause-and-effect approach with definite beneficial outcomes whereas ecosystem management may be a more difficult concept to apply because there are often multiple and indirect causes-and-effects interacting over time and space)

Because of these often overriding political, social, institutional, economic, and technical limitations, most habitat alteration projects focus on activities that can be undertaken within the active channel (i.e., between streambanks). And by doing so, they perpetuate and reinforce a "channel vision" perspective. In contrast to an ecosystem perspective, a channel approach tends to focus solely on physical habitat components and has dominated stream habitat projects for decades.

Streambanks and channels that have been "hardened" by structural additions can lose their capability to respond and dampen the continually changing flow and sediment regimes of natural stream systems. Conversely, when channel changes occur after structural treatments have been applied, the effects to stream systems, channel morphology, soils, and vegetation can be

substantial (Frizzell and Nawa 1992). A dramatic example of such changes occurred in Meadow Creek, a tributary to the Grand Ronde River in eastern Oregon, after large amounts of large woody debris were added to a reach that had been previously impacted by logging and long-term grazing. During a large flow event, the majority of these structures were displaced downstream and contributed to a major loss of riparian soils and redistribution of stream gravels (Beschta et al. 1992). While vegetation recovery has been encouraging following the high flow event and the cessation of grazing, the loss of riparian soils may affect the ultimate capability of this riparian/aquatic system to recover.

Many structural features are placed in stream systems where they are geomorphically inappropriate (e.g., the use of boulder or wood in stream systems where such materials never occurred naturally). In other instances, the use of gabions, tires, geotexile fabrics, or other foreign materials have been used. It is ironic that foreign or artificial habitats are being implemented to save wild or native fish populations.

> "Pouring time and money into a degraded stream that is continuously perturbed by human land use activities is not only futile, but it raises false public expectations that aquatic conditions will be improving."

Ecosystem management concepts are increasingly being discussed and implemented with regard to a wide range of forest land and animal species, including aquatic components (FEMAT 1993). However, these concepts have not been incorporated in the vast majority of stream improvement or restoration projects. Similarly, ecosystem approaches to the management of rangeland, agricultural, and urban stream systems are not prevalent at present.

CASE HISTORIES

The original paper includes 7 pages summarizing the results of studies and recent field reviews of fisheries enhancement and restoration projects including Oregon streams (Fish Creek, the Grand Ronde and John Day River basins, Fifteenmile Creek, and Trout Creek Basins), Idaho structural activities (natural barrier removal, riparian revegetation and sediment reduction, instream structures, and off-channel developments), Utah (Big Creek), Arizona, New Mexico, and California (Mono Basin streams). Refer to the original paper for complete details.

WHAT WORKS AND WHAT NEEDS FIXING

Increasingly, the realization is developing in the scientific community that complex ecosystems and associated habitat features cannot be achieved via the simple and artificial manipulation of selected components. For example, the habitat deficiencies associated with low numbers of pools in a stream cannot be simply satisfied by digging more pools. Instead, the functional attributes of the entire system need to be reestablished along with the appropriate physical, chemical, and biological processes. Thus, habitat restoration "..is a holistic process not achieved through the isolated manipulation of individual elements" (National Research Council 1992). Furthermore, the objective of restoration "..is to emulate a natural, self-regulating system that is integrated ecologically with the landscape in which it occurs" (National Research Council 1992). Herein lies a basic conflict associated with most structural programs of habitat alteration. Structural approaches usually have short-term objectives (i.e., stabilize a streambank or create a pool) but fall far short of the long-term ecological requirements of habitat restoration. Structures often do not create features associated with intact riparian plan communities.

An ecological view of habitat restoration requires not only a long-term perspective, but a comprehensive understanding of riparian/aquatic

systems. Such concepts as hydrogeomorphic disturbance patterns, patterns of vegetation establishment and succession, use of reference sites, and an understanding of land use history are generally needed to assist in identifying restoration needs. Perhaps even more importantly, without the removal or significant reduction of anthropogenic activities that are currently having adverse impacts to riparian/aquatic ecosystems, the restoration of aquatic habitats for fisheries and other organisms cannot be expected.

Many studies and field reviews of fisheries enhancement projects (refer to the original paper for details) echo several common themes.

CONCLUSIONS AND RECOMMENDATIONS

- The removal or elimination of land use activities that cause adverse impacts to riparian and aquatic ecosystems are of the highest priority if restoration is to be accomplished.
- Abusive land use practices cannot be mitigated by structural additions or modifications to stream channels.
- The restoration of healthy riparian vegetation is a necessary requirement for improving a wide range of riparian functions and aquatic habitats; such restoration requires that the dynamic processes of establishment, growth, and succession of riparian plant communities be allowed to occur.
- Natural disturbance patterns and processes (e.g., high flows and sediment transport) are an important component of riparian/aquatic ecosystems; they interact in non-deterministic ways with vegetation and channel morphology during the restoration of functional riparian/aquatic systems and habitats.
- Ecological recovery and improvement requires time for the influence and functions of riparian vegetation to be expressed in conjunction with natural disturbance regimes, thus restoration requires a long-term perspective.
- Projects which relied on the use of instream structures often severed ecological linkages between terrestrial, riparian and aquatic ecosystems; because of their size and permanence, many of these structures will cause a long-term shift in channel morphology and loss of instream functions.
- Even though major enhancement programs have been underway for 10 years or more, rigorous monitoring or evacuation has seldom been initiated or accomplished, thus their biological importance for improving or sustaining fisheries productivity has seldom been documented.
- Existing monitoring of fish population trends has not provided evidence that structural approaches to improving fish habitat are attaining desired goals.
- The use of non-natural materials (e.g., goetextiles) should be eliminated from instream projects directed at improving or enhancing the habitats of wild or native fishes.

Restoration of aquatic habitats is obviously a critical need for streams throughout the American West. However, efforts should focus on those streams in which the potential to return to a near natural state is possible (Platts and Rinne 1985). Furthermore, artificial stream enhancement cannot be utilized to circumvent the causations of stream degradation. In other words, artificial structures are not a suitable alternative or mitigating factor to land use activities which degrade riparian ecosystems. If abusive land use practices are creating habitat degradation, the alteration or elimination of those practices should be undertaken with a sense of urgency. This is clearly the first and most important step in riparian/aquatic restoration (Figure 1). Pouring time and money into a degraded stream that is continuously perturbed by human land use activities is not only futile, but it raises false public expectations that aquatic conditions will be improving.

The rationale behind many stream habitat projects appears to parallel that of trout-stocking programs. These expensive put-and-take

operations have facilitated a fishing experience by the public, even in extremely degraded streams. Unfortunately, put-and-take stocking programs thus become a substitute for good land and water stewardship at the expense of native fisheries and the inherent biological diversity of western riparian/stream ecosystems. Artificial stream restoration must never substitute for a vigorous, responsible stewardship of riparian systems and their surrounding watershed.

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Copies of the entire paper are available by writing:
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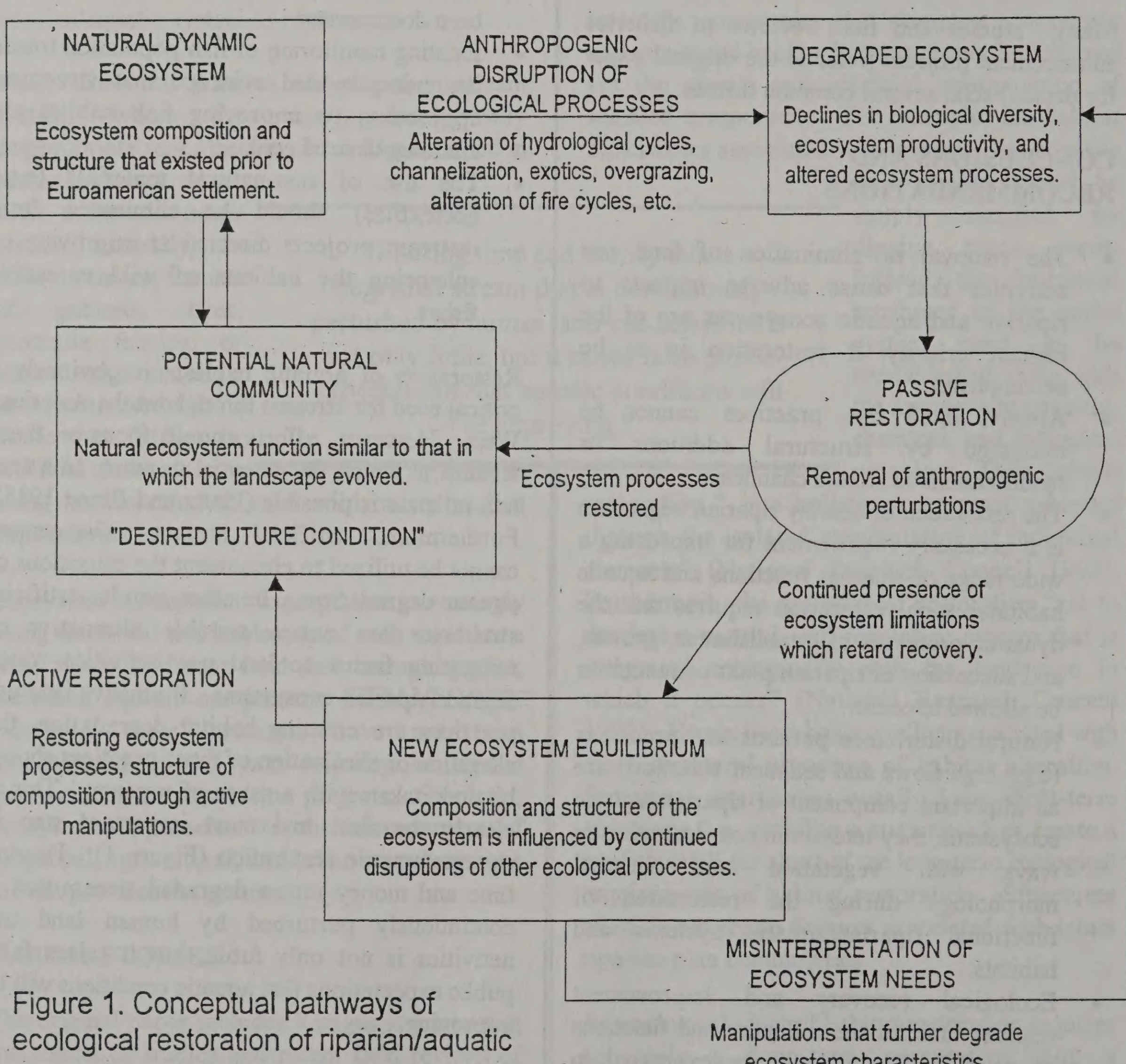

Figure 1. Conceptual pathways of ecological restoration of riparian/aquatic ecosystems (After Kauffman et al. 1993)

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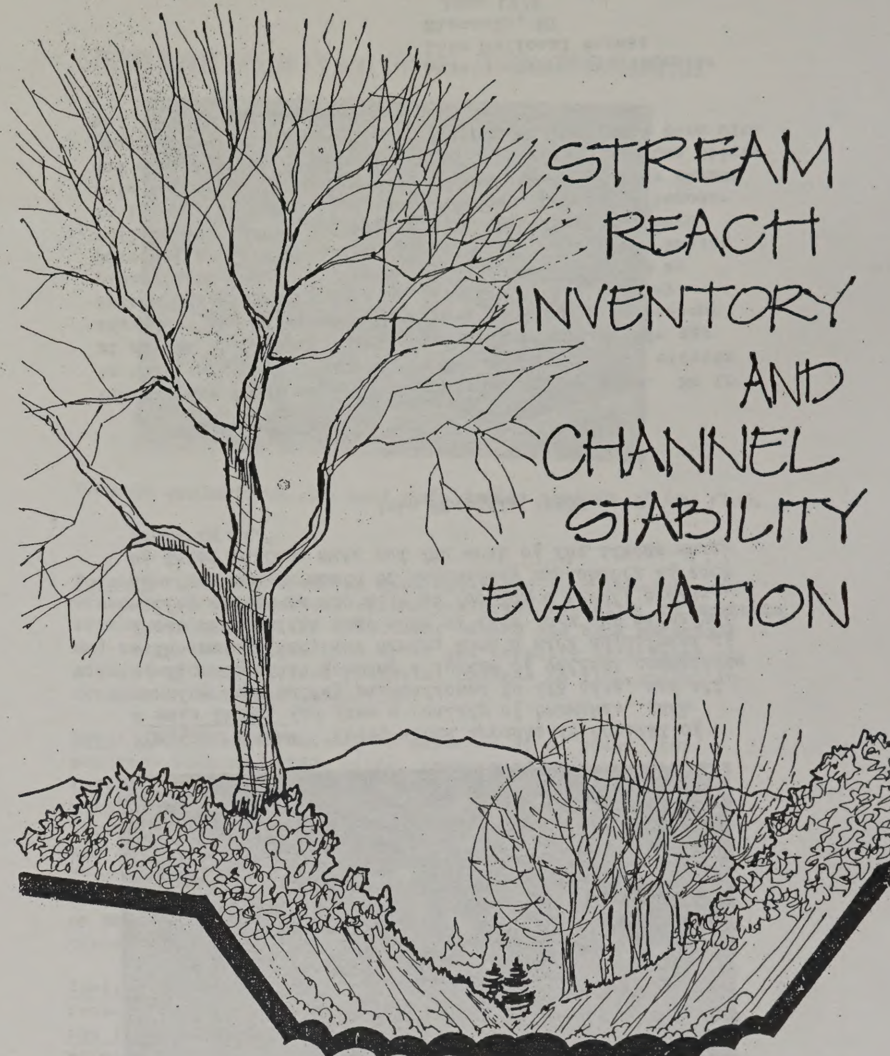


STREAM REACH INVENTORY AND CHANNEL STABILITY EVALUATION

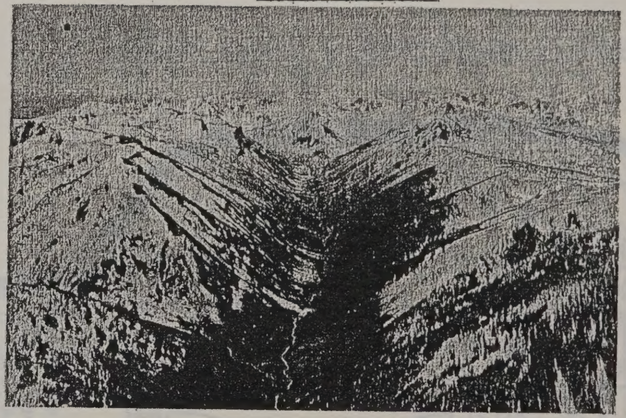
A Watershed Management Procedure

United States Department of Agriculture

Forest Service Northern Region

INDEX

ACKNOWLEDGEMENTS



Playfair's Law: "Every river appears to consist of a main trunk, fed from a variety of branches, each running in a valley proportioned to its size, and all of them together forming a system of valleys connecting with one another, and having such a nice adjustment of their declivities that none of them join the principal valley either on too high or too low a level; a circumstance which would be infinitely improbable if each of these valleys were not the work of the stream which flows in it."

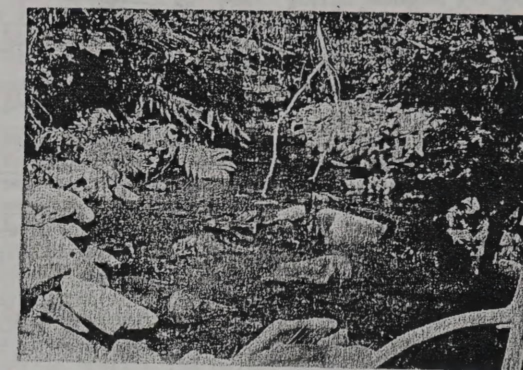
John Playfair, 1802

Others have built on John Playfair's observations. So it is with this work. Dr. Walter Megahan's original efforts at stream channel characterization in Utah a decade ago served as the stimulus. From that beginning the present system has evolved as a team effort. It has been my pleasure to shephard this work and contribute from my personal experience and observations. My Northern Region colleagues, past and present, have contributed so much in the way of suggestions and critique that it is impossible now to say "this is his and this is mine". My thanks and appreciation go especially to Dave Rosgen and Lee Silvey who labored through several revisions of the field form with me. Now the ball passes to you. Take it and run!

Dale J. Pfankuch, Forester
Lolo National Forest
Missoula, MT
June 1978

Presently Hydrologist
Rocky Mountain Region, Denver, CO

STREAM REACH INVENTORY AND CHANNEL STABILITY EVALUATION



Channel evaluations are best made during periods of low flow.

Purpose: These procedures were developed to systemize measurements and evaluations of the resistive capacity of mountain stream channels to the detachment of bed and bank materials and to provide information about the capacity of streams to adjust and recover from potential changes in flow and/or increases in sediment production.

Uses: The information may be gathered at a "point" for projects such as bridge sites, campground, etc., or in complete channel analyses for fisheries, timber management water balance or multiple use inventories and planning. Stream reaches may be stratified by order and geologic type and sampled to an intensity that meets survey requirements. "Point" as used here always means a reach of sufficient length to provide the observer with a range of information on which to base a sound selection from available alternatives.

Instructions: The card format of R-1 Form 2500-5A and this pocket field guidebook are designed to be used together - in the field. Use a separate rating card for each length of stream that appears similar. Identify the reach on Card Form 2500-5A, on maps and/or photos in sufficient detail so others can locate the same reach at some future time.

The inventory items are completed using maps, aerial photos and field observations and measurements. Circle all estimated data items that could be measured but weren't. The precision of measurements will be dictated by the requirements of the particular inventory. These standards should be clearly in mind when the work begins.

The evaluation portion of the inventory requires judgement based on experience and the criteria outlined in this booklet. The condition descriptions, briefly explained on the tally form, are amplified in more detail in the pages that follow. As you begin the evaluation phase of the inventory, a few words of caution are in order. Avoid keying in on a single indicator or a small group of indicators in making ratings. Since the indicators are interrelated, don't dwell on any one item for long. If all are used without bias, the maximum diagnostic value can be obtained. Do the best you can. Experience has shown that over and underratings tend to balance out. Total rating scores made by inexperienced persons are often numerically close to the scores of those with more experience.

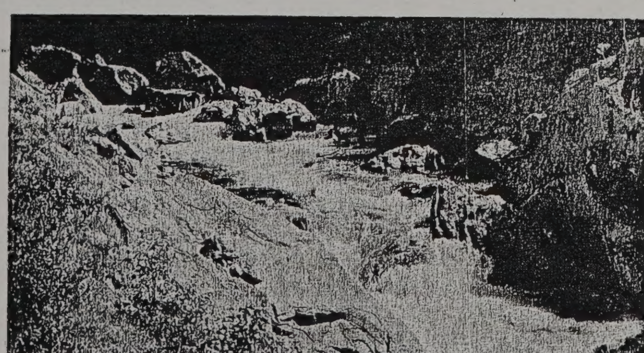
Keep in mind that each item directly or indirectly is designed to answer three basic questions:

1. What are the magnitudes of the hydraulic forces at work to detach and transport the various organic and inorganic bank and channel components?

2. How resistent are these components to the recent stream flow forces exerted on them?

3. What is the capacity of the stream to adjust and recover from potential changes in flow volume and/or increases in sediment production?

The channel and adjacent flood plain banks are subjectively rated, item by item, following an on-the-ground inspection. Circle only one of the numbers in parentheses for each item rated. If actual conditions fall somewhere between the conditions as described, cross out the number given and below it write in an intermediate value which better expresses the situation as you see it.



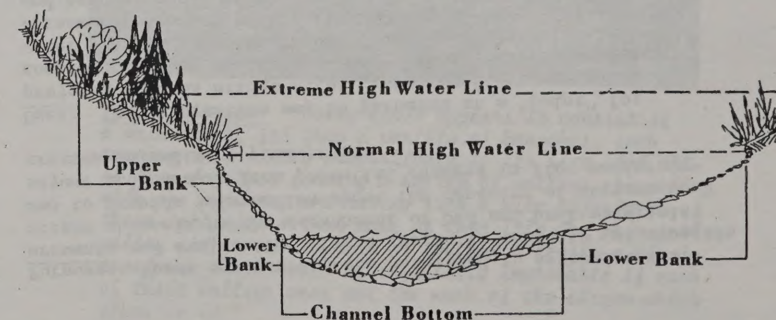
NOTE: Channels cut to bedrock are always rated Excellent.

DEFINITION OF TERMS AND ILLUSTRATIONS

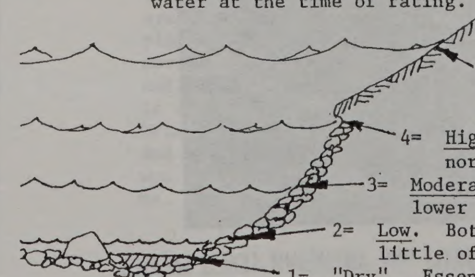
Upper Bank - That portion of the topographic cross section from the break in the general slope of the surrounding land to the normal high water line. Terrestrial plants and animals normally inhabit this area.

Lower Banks - The intermittently submerged portion of the channel cross section from the normal high water line to the water's edge during the summer low flow period.

Channel Bottom - The submerged portion of the channel cross section which is totally an aquatic environment.



Stream Stage - The height of water in the channel at the time of rating is recorded, using numbers 1 through 5. These numbers, as shown below, relate to the surface water elevation relative to the normal high water line. A decimal division should be used to more precisely define conditions, i.e., 3.5 means 3/4ths of the channel banks are under water at the time of rating.



5= Flooding. The flood plain is completely covered.

4= High. Channel full to the normal high water line.

3= Moderate. Bottom and 1/2 of lower banks wetted.

2= Low. Bottom covered but very little of the lower banks wet.

1= "Dry". Essentially no flow. Water may stand in bottom depressions.

KEY CARD FOR FIELD FORM 2500-5A

KEY NUMBER ON FIELD CARDS

Group	Item Rated	Key
Upper Banks	Landform Slope	1
Upper Banks	Mass Wasting or Failure (existing or potential)	2
Upper Banks	Debris Jam Potential (Floatable Objects)	3
Upper Banks	Vegetative Bank Protection	4
Lower Banks	Channel Capacity	5
Lower Banks	Bank Rock Content	6
Lower Banks	Obstructions Flow Deflectors Sediment Traps	7
Lower Banks	Cutting	8
Lower Banks	Deposition	9
Bottom	Rock Angularity	10
Bottom	Brightness	11
Bottom	Consolidation or Particle Packing	12
Bottom	Bottom Size Distribution and Percent Stable Materials	13
Bottom	Scouring and Deposition	14
Bottom	Clinging Aquatic Vegetation (Moss and Algae)	15

R-1 STREAM REACH INVENTORY and CHANNEL STABILITY EVALUATION

REACH LOCATION: Survey Date 8-12-75 Time 1430 Obs. D.R. - L.S. - D.P.

Forest Brightwater Rgr. Dist. Purity

Stream Fern Creek P.W.I. W/S No. 16-02-00-04-23-05-01-01

Reach Description & Other Identification Road crossing Sec 3 to 1/4 mi. upstream Aerial Photo #274-191

	Key #	Stability Indicators by Classes EXCELLENT		(Fair and Poor on reverse side) GOOD	
Upper Banks	1	Bank slope gradient <30%.	(2)	Bank slope gradient 30-40%.	(4)
Upper Banks	2	No evidence of past or any potential for future mass wasting into channel.	(3)	Infrequent and/or very small. Mostly healed over. Low future potential.	(6)
Upper Banks	3	Essentially absent from immediate channel area.	(2)	Present but mostly small twigs and limbs.	(4)
Upper Banks	4	90%+ plant density. Vigor and variety suggests a deep, dense, soil binding, root mass.	(3)	70-90% density. Fewer plant species or lower vigor suggests a less dense or deep root mass.	(6)
Lower Banks	5	Ample for present plus some increases. Peak flows contained. W/D ratio <7.	(1)	Adequate. Overbank flows rare. Width to Depth (W/D) ratio 8 to 15.	(2)
Lower Banks	6	65%+ with large, angular boulders 12"+ numerous.	(2)	40 to 65%, mostly small boulders to cobbles 6-12".	(4)
Lower Banks	7	Rocks and old logs firmly embedded. Flow pattern without cutting or deposition. Pools and riffles stable.	(2)	Some present, causing erosive cross currents and minor pool filling. Obstructions and deflectors newer and less firm.	(4)
Lower Banks	8	Little or none evident. Infrequent raw banks less than 6" high generally.	(4)	Some, intermittently at outcurves and constrictions. Raw banks may be up to 12".	~~(8)~~ 6
Lower Banks	9	Little or no enlargement of channel or point bars.	(4)	Some new increase in bar formation, mostly from coarse gravels.	(8)
Bottom	10	Sharp edges and corners, plane surfaces roughened.	(1)	Rounded corners and edges, surfaces smooth and flat.	(2)
Bottom	11	Surfaces dull, darkened, or stained. Gen. not "bright".	(1)	Mostly dull, but may have up to 35% bright surfaces.	(2)
Bottom	12	Assorted sizes tightly packed and/or overlapping.	(2)	Moderately packed with some overlapping.	(4)
Bottom	13	No change in sizes evident. Stable materials 80-100%.	(4)	Distribution shift slight. Stable materials 50-80%.	(8)
Bottom	14	Less than 5% of the bottom affected by scouring and deposition.	(6)	5-30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	(12)
Bottom	15	Abundant. Growth largely moss-like, dark green, perennial. In swift water too.	(1)	Common. Algal forms in low velocity & pool areas. Moss here too and swifter waters.	(2)
		EXCELLENT COLUMN TOTAL →	24	GOOD COLUMN TOTAL →	22

Add values in each column and record in spaces below. Add column scores.

E 24 + G. 22 + F. 6 + P. 0 = 52 Total Reach Score.

Adjective ratings: <38=Excellent, 39-76=Good, 77-114=Fair, 115+=Poor*

*(Scores above may be locally adjusted by Forest Hydrologist)

R1-Form 2500-5A Rev.1-75 Side 1.

INVENTORY DATA: (observed or measured on this date) Side 2

Stream Width 6 ft.X Ave.Depth 0.5 ft.X Ave.Velocity 1.2 /s= 3.6 Flow cfs
Reach Gradient 4 %; Stream Order 3 . Turbidity Level Low . Stream Stage Low(2.3) Sinuosity Ratio 1.2 .
Temperature °F or °C of: Air 86 Water 52 . Others pH 7.2 , Conductance 45 μMhos
Water Quality Sample Bottle # 34

	Key #	Stability Indicators by Classes FAIR		POOR	
Upper Banks	1	Bank slope gradient 40-60%.	(6)	Bank slope gradient 60%+.	(8)
	2	Moderate frequency & size, with some raw spots eroded by water during high flows.	(9)	Frequent or large, causing sediment nearly yearlong OR imminent danger of same.	(12)
	3	Present, volume and size are both increasing.	(6)	Moderate to heavy amounts, predominantly larger sizes.	(8)
	4	50-70% density. Lower vigor and still fewer species form a somewhat shallow and discontinuous root mass.	(9)	<50% density plus fewer species & less vigor indicate poor, discontinuous, and shallow root mass.	(12)
Lower Banks	5	Barely contains present peaks. Occassional overbank floods. W/D ratio 15 to 25.	(3)	Inadequate. Overbank flows common. W/D ratio > 25.	(4)
	6	20 to 40%, with most in the 3-6" diameter class.	(6)	< 20% rock fragments of gravel sizes, 1-3" or less.	(8)
	7	Moderately frequent, moderately unstable obstructions & deflectors move with high water causing bank cutting and filling of pools.	(6)	Frequent obstructions and deflectors cause bank erosion yearlong. Sediment traps full, channel migration occurring.	(8)
	8	Significant. Cuts 12"-24" high. Root mat overhangs and sloughing evident.	(12)	Almost continuous cuts, some over 24" high. Failure of overhangs frequent.	(16)
	9	Moderate deposition of new gravel & coarse sand on old and some new bars.	(12)	Extensive deposits of predominantly fine particles. Accelerated bar development.	(16)
Bottom	10	Corners & edges well rounded in two dimensions.	(3)	Well rounded in all dimensions, surfaces smooth.	(4)
	11	Mixture, 50-50% dull and bright, ± 15% ie. 35-65%.	(3)	Predominantely bright, 65%+, exposed or scoured surfaces.	(4)
	12	Mostly a loose assortment with no apparent overlap.	(6)	No packing evident. Loose assortment, easily moved.	(8)
	13	Moderate change in sizes. Stable materials 20-50%.	(12)	Marked distribution change. Stable materials 0-20%.	(16)
	14	30-50% affected. Deposits & scour at obstructions, constrictions, and bends. Some filling of pools.	(18)	More than 50% of the bottom in a state of flux or change nearly yearlong.	(24)
	15	Present but spotty, mostly in backwater areas. Seasonal blooms make rocks slick.	(3)	Perennial types scarce or absent. Yellow-green, short term bloom may be present.	(4)
		FAIR COLUMN TOTAL →	6	POOR COLUMN TOTAL →	0

Size Composition of Bottom Materials (Total to 100%)

1. Exposed bedrock........... 0 %	5. Small rubble, 3"-6"..... 30 %
2. Large boulders, 3'+ Dia.... 5 %	6. Coarse gravel, 1"-3".... 25 %
3. Small boulders, 1-3'....... 10 %	7. Fine gravel, 0.1-1"..... 20 %
4. Large rubble, 6"-12"....... 10 %	8. Sand, silt, clay, muck.. T %

Amplification of the Stream Channel Evaluation Items

General

Space on the field form permits only the very briefest description of the various components. This field booklet provides, in the text which follows, some of the basic rationale in support of these brief "kernels" or core thoughts. These explanations are arranged in the same order as they appear on the field form.

The channel cross section is subdivided into three components, to focus your attention on the various indicators to be subjectively evaluated. Once again, you are cautioned not to "key in" on any one item or group of items. All that have been included are interralated and all must be used in an unbiased way to achieve consistent evaluations of the current situation.

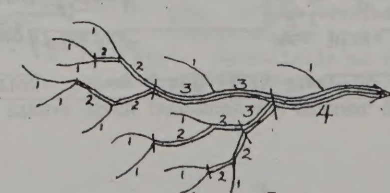
Stream channel ratings should not be attempted without the preparation provided by this Field Guide. The language of the text has been kept rather general to avoid limiting its use as a management tool to a small geographic area. These general descriptions, coupled with your local experience, will stimulate mental images of indicator conditions which, when shared with fellow workers, will lead to consistent, reproducible ratings.

Illustrations in the text should be considered general in nature and not specific for all situations. It is suggested that local conditions be photographed and the pictures added to this Field Guide to achieve local uniformity.

A word of additional caution: Keep the scale of the reach being evaluated in context with the scale of dimensions given in the text and on the inventory form. Rating items were taylored for and best fit the 2nd to 4th order stream reaches. Very small, unbranched, first order segments will require a scaling down of sizes while the larger stream and river reaches will require some mental enlargement of the criteria given to fit the situation.

STREAM ORDER CLASSIFICATION

First order streams are unbranched reaches found usually but not exclusively at the head of drainage basins. Second order reaches are formed when two or more first order reaches come together and so on as illustrated below.



I. Upper Channel Banks

The land area immediately adjacent to the stream channel is normally and typically a terrestrial environment. Landforms vary from wide, flat, alluvial flood plains to the narrow, steep termini of mountain slopes. Intermittently this dry land flood plain becomes a part of the water course. Forces of velocity and turbulence tear at the vegetation and land. These hydraulic forces, while relatively short lived, have great potential for producing onsite enlargements of the stream channel and downstream sedimentation damage. Resistance of the component elements on and in the bank are highly variable. This section is designed to aid in rating this relative resistence to detachment and transport by floods.

A. Landform Slope: The steepness of the land adjacent to the stream channel determines the lateral extent and ease to which banks can be eroded and the potential volume of slough which can enter the water. All other factors being equal, the steeper the land adjacent to the stream, the greater the potential volume of slough materials.

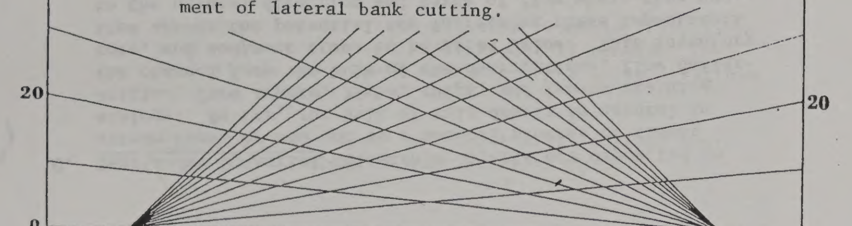
The 60% limit for poor was selected as a conservative gravitational repose angle for unconsolidated soil materials. Slopes steeper than this are rated poor because they would erode into the stream by gravity alone, if denuded of their protecting vegetation. The other ratings built on this limit and are arbitrarily set as follows:

1. Excellent: Side slopes to the channel are generally less than 30 percent on both banks.

2. Good: Side slopes up to 40% on one or occasionally both banks.

3. Fair: Side slopes to 60% common on one or both banks.

4. Poor: Steep slopes, over 60%, provide larger volumes of soil for downstream sedimentation for each increment of lateral bank cutting.



PERCENT SLOPE SCALE

Hold this page at arms length..match the slope of the topography with the percent slope lines on the scale above.

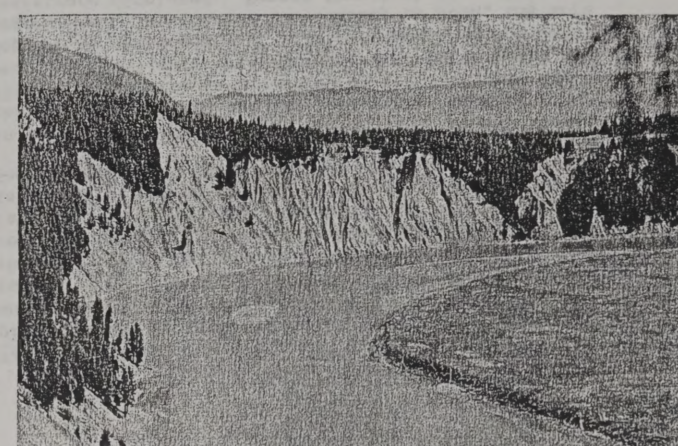
B. Mass Wasting Hazard This rating involves existing or potential detachment from the soil mantle and downslope movement into waterways of relatively large pieces of ground. Mass movement of banks by slumping or sliding introduces large volumes of soil and debris into the channel suddenly, causing constrictions or complete damming followed by increased stream flow velocities, cutting power and sedimentation rates. Conditions deteriorate in this element with proximity, frequency and size of the mass wasting areas and with progressively poorer internal drainage and steeper terrain:

1. Excellent: There is no evidence of mass wasting that has or could reach the stream channel.

2. Good: There is evidence of infrequent and/or very small slumps. Those that exist may occasionally be "raw" but predominately the areas are revegetated and relatively stable.

3. Fair: Frequency and/or magnitude of the mass wasting situation increases to the point where normal high water aggravates the problem of channel changes and subsequent undercutting of unstable areas with increased sedimentation.

4. Poor: Mass wasting is not difficult to detect because of the frequency and/or size of existing problem areas or the proximity of banks are so close to potential slides that any increases in the flow would cut the toe and may trigger slides of significant size to cause downstream water quality problems for a number of years.



Mass wasting of slopes directly into the stream channel.

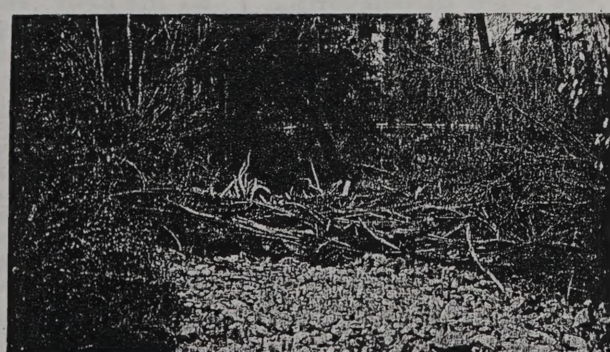
C. Debris Jam Potential Floatable objects are deposited on stream banks by man and as a natural process of forest ecology. By far, the bulk of this debris is natural in origin. Tree trunks, limbs, twigs, and leaves reaching the channel form the bulk of the obstructions, flow deflectors, and sediment traps to be rated below. This inventory item assess the potential for increasing these impediments to the natural direction and force of flow where they now lay. It also includes the possibility of creating new debris jams under certain flow conditions.

1. Excellent: Debris may be present on the banks, but is so situated or is of such a size, that the stream is not able to push or float it into the channel and, therefore, for all intents and purposes, it is absent. In truth, there may be none physically present. Both situations are rated the same.

2. Good: The debris present offers some bank protection for a while but is small enough to be floated away in time. Only small jams could be formed with this material alone.

3. Fair: There is a noticeable accumulation of all sizes and the stream is large enough to float it away, at certain times, thus decreasing the bank protection and adding to the debris jam potential downstream.

4. Poor: Moderate to heavy accumulations are present due to fires, insect attack, disease mortality, windthrow, or logging slash. High flows will float some debris away and the remainder will cause channel changes.



A series of debris jams of small size materials like the one shown in the center of this photo cause this item to be rated "Poor".

D. Vegetative Bank Protection: The soil in banks is held in place largely by plant roots. Riparian plants have almost unlimited water for both crown and root development. Their root mats generally increase in density with proximity to the open channel. Trees and shrubs generally have deeper root systems than grasses and forbs. Roots seldom extend far into the water table, however, and near the shore of lakes and streams they may be comparatively shallow rooted. Some species are, therefore, subject to windthrow.

In addition to the benefits of the root mat in stabilizing the banks, the stems help to reduce the velocity of flood flows. Turbulence is generated by stems in what may have been laminar flow. The seriousness of this energy release depends on the density of both overstory and understory vegetation. The greater the density of both, the more resistence displayed. Damage from turbulence is greatest at the bank edge and diminishes with distance from the normal channel. Other factors to consider, in addition to the density of stems, are the varieties of vegetation, the vigor of growth and the reproduction processes. Vegetal variety is more desirable than a monotypic plant community. Young plants, growing and reproducing vigorously, are better than old, decadent stands.

1. Excellent: Trees, shrubs, grass and forbs combined cover more than 90 percent of the ground. Openings in this nearly complete cover are small and evenly dispersed. A variety of species and age classes are represented. Growth is vigorous and reproduction of species in both the under- and over-story is proceeding at a rate to insure continued ground cover conditions. A deep, dense root mat is inferred.
2. Good: Plants cover 70 to 90 percent of the ground. Shrub species are more prevalent than trees. Openings in the tree canopy are larger than the space resulting from the loss of a single mature individual. While the growth vigor is generally good for all species, advanced reproduction may be sparse or lacking entirely. A deep root mat is not continuous and more serious erosive incursions are possible in the openings.
3. Fair: Plant cover ranges from 50 to 70 percent. Lack of vigor is evident in some individuals and/or species. Seedling reproduction is nil. This condition is ranked fair, based primarily on the percent of the area not covered by vegetation with a deep root mat potential and less on the kind of plants that make up the overstory.
4. Poor: Less than 50 percent of the ground is covered. Trees are essentially absent. Shrubs largely exist in scattered clumps. Growth and reproduction vigor is generally poor. Root mats discontinuous and shallow.

II. Lower Channel Banks

The channel zone is located between the normal high water and low water lines. Both aquatic and terrestrial plants may grow here but normally their density is sparse.

The lower channel banks define the present stream width. Stability of these channel banks is indicated under a given flow regimen by minor and almost imperceptable changes in channel width from year to year. In other words, encroachment of the water environment into the land environment is nil.

Under conditions of increasing channel flow, the banks may weaken and both cutting (bank encroachment) and deposition (bank extension) begin, usually at bends and points of constriction. Cutting is evidenced by steepening of the lower banks. Eventually the banks are undercut, followed by cracking and slumping. Deposition behind rocks or bank protrusions increase in length and depth.

As the channel is widened, it may also be deepened to accommodate the increased volume of flow. For convenience only, changes of channel bottoms are observed separately and last in this evaluation scheme.

5

A. Channel Capacity: Channel width, depth, gradient, and roughness determine the volume of water which can be transmitted. Over time channel capacity has adjusted to the size of watershed above the reach rated, to climate, and to changes of vegetation. Some indicators of change are widening and/or deepening of the channel which affects the ratio of width to depth. When the capacity is exceeded, deposits of soil are found on the banks and organic debris may be found hung up in the bank vegetation. These are expressions of the most recent flood event. Indicators of conditions as recent as a year or two ago may be difficult or impossible to find, but do your best to estimate what normal peak flows are and whether the present cross section is adequate to handle the load without bank deterioration.

1. Excellent: Cross sectional area is ample for present peak volumes plus some additional, if needed. Overbank floods are rare. Width to depth ratio less than 7; i.e., (36' wide ÷ 6' deep = 6).

2. Good: Adequate cross sectional area contains most peak flows. Width to depth ratio 8 to 15.

3. Fair: Channel barely contains the peak runoff in average years or less. Width to depth ratios range from 15 to 25.

4. Poor: Channel capacity generally inadequate. Overbank floods quite common as indicated by kind and condition of the bank plants and the position and accumulation of debris. Width to depth ratio 25 or more.

6

B. Bank Rock Content: Examination of the materials that make up the channel bank will reveal the relative resistence of this component to detachment by flow forces. Since the banks are perennially and intermittently both aquatic and terrestrial environments, these sites are harsh for most plants that make up both types. Vegetation is, therefore, generally lacking and it is the volume, size and shape of the rock component which primarily determine the resistence to flow forces.

A soil pit need not be dug. Surface rock and exposed cut banks—will enable you to categorize this item as listed by percentage ranges on the field form.

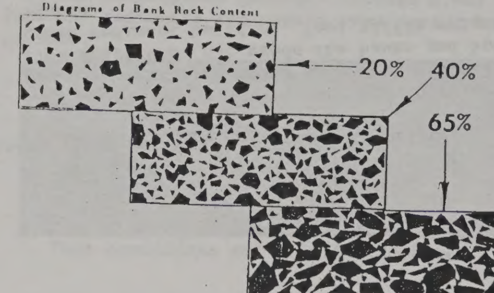
1. Excellent: Rock makes up 65% or more of the volume of the banks. Within this rock matrix large, angular boulders 12" (on their largest axis) are numerous.

2. Good: Banks 40-65% rock which are mostly small boulders and cobble ranging in size from 6-12" mean diameter. Some may be rounded while others are angular.

3. Fair: 20-40% of bank volume rock. While some big rock may be present, most fall into the 3-6" diameter class.

4. Poor: Less than 20% rock fragments, mostly of gravel sizes 1-3" in diameter.

Diagrams of Bank Rock Content



7. C. Obstructions and Flow Deflectors: Objects within the stream channel, like large rocks, embedded logs, bridge pilings, etc., change the direction of flow and sometimes the velocity as well. Obstructions may produce adverse stability effects when they increase the velocity and deflect the flow into unstable and unprotected banks and across unstable bottom materials. They also may produce favorable impacts when velocity is decreased by turbulence and pools are formed.

Sediment Traps: Channel obstructions which dam the flow partly or wholly form pools or slack water areas. The pools lower the channel gradient. With this loss of energy the sediment transport power is greatly reduced. Coarse particles drop out first at the head of the pool. Some or all of the fine suspended particles may carry on through.

Embedded logs and large boulders can produce very stable natural dams which do not add to channel instability. Some debris dams and beaver dams, however, are quite unstable and only serve to increase the severity of channel damage when they break up.

The effectiveness of these sediment traps depends on pool length relative to entrance velocity. The swifter the current, the longer the pool needed to reach zero velocity. Turbulence caused by a falls at the head of the pool shortens the length required to reach zero velocity.

How long these traps are effective depends on depth and width as well as pool length and, of course, the rate of sediment accretion.

Items of vegetation growing in the water, like alders, willows, cattails, reeds, and sedges are also effective traps in some locations and reduce flow velocity and sediment carrying power.

Overturned shoreline trees become obstructions and flow deflectors as shown here. If frequent in the reach, rate this item "Poor".

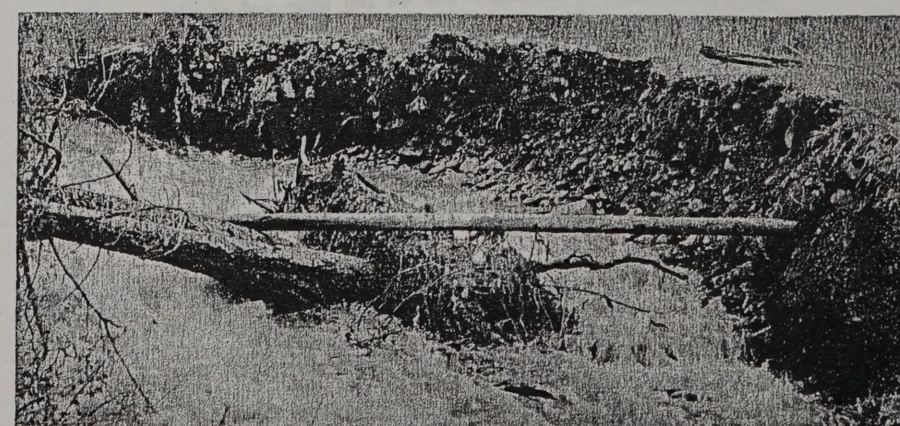
C. Obstructions and Flow Deflectors (Continued)

1. Excellent: Logs, rocks, and other obstructions to flow are firmly embedded and produce a pattern of flow which does not erode the banks and bottom or cause sediment buildups. Pool riffle relationship stable.

2. Good: Obstructions to flow and sediment traps are present, causing cross currents which create some minor bank and bottom erosion. Some of the obstructions are newer, not firmly embedded and move to new locations during high flows. Some sediment is trapped in pools decreasing their capacity.

3. Fair: Moderately frequent and quite often unstable obstructions, cause noticeable seasonal erosion of the channel. Considerable sediment accumulates behind obstructions.

4. Poor: Obstructions and traps so frequent they are intervisible, often unstable to movement and cause a continual shift of sediments at all seasons. Since traps are filled as soon as formed, the channel migrates and widens.



Same location as shown on page 14, but looking upstream. Obstruction like this could become the nucleus of a debris jam.

8

Cutting and Deposition are concommittent processes. You can't have one without the other. However, it is possible for each to be taking place in different reaches of the same stream at the same time, and hence the separation for classification purposes which follows.

D. Cutting: One of the first signs of channel degradation would be a loss of aquatic vegetation by scouring or uprooting. Some channels are naturally devoid of aquatic plants and here the first stages would be an increase in the steepness of the channel banks. Beginning near the top, and later extending in serious cases to the total depth, the lower channel bank becomes a near vertical wall.

If plant roots bind the surface horizon of the adjacent upper bank into a cohesive mass, undercutting will follow. This process continues until the weight of overhang causes the sod to crack and subsequently slump into the channel. Differential horizontal compaction and texture could also result in undercut banks even with an absence of vegetative cover. There are some loosely consolidated banks that with or without vegetation are literally nibbled away, never developing much, if any, overhang.

1. Excellent: Very little or no cutting is evident. Raw, eroding banks are infrequent, short and predominately less than 6" high.

2. Good: Some intermittent cutting along channel outcurves and at prominent constrictions. Eroded areas are equivalent in length to one channel width or less and the vertical cuts are predominately less than 12".

3. Fair: Significant bank cutting occurs frequently in the reach. Raw vertical banks 12" to 24" high are prevalent as are root mat overhangs and sloughing.

4. Poor: Nearly continuous bank cutting. Some reaches have vertical cut faces over 2 feet high. Undercutting, sod-root overhangs and vertical side failures may also be frequent in the rated reach.

Poor bank conditions at this bend are evident.

9

E. Deposition: Lower bank channel areas are generally the steeper portions of the wetted perimeter and may be rather narrow strips of land that offer slight opportunity for deposition. Exceptions to this statement abound since deposition is often noted on the lee side of large rocks and log deflectors which form natural jetties. However, these deposits tend to be short and narrow. On the less steep, lower banks, deposition during recession from peak flows can be quite large. The appearance of sand and gravel bars where they did not previously exist may be one of the first signs of upstream erosion. These bars tend to grow, primarily in depth and length, with continued watershed disturbance(s). Width changes are in a shoreward direction as overflow deposition takes place on the upper banks. Dimensional deposition "growth" is limited by the size and orientation of the obstructions to flow along the channel banks, flow velocity and a continuing upstream sediment supply.

Deposition may also occur on the inside radii of bends, particularly if active cutting is taking place on the opposite shore. Also, deposits are found below constrictions or where there is a sudden flattening of stream gradient as occurs upstream above geologic nic points.

1. Excellent: Very little or no deposition of fresh silt, sand or gravel in channel bars in straight reaches or point bars on the inside banks of curved reaches.

2. Good: Some fresh deposits on bars and behind obstructions. Sizes tend to be predominately from the larger size classes - coarse gravels.

3. Fair: Deposits of fresh, coarse sands and gravels observed with moderate frequency. Bars are enlarging and pools are filling so riffle areas predominate.

4. Poor: Extensive deposits of predominately fresh, fine sands, some silts, and small gravels. Accelerated bar development common. Storage areas are now full and sediments are moving even during low flow periods.

Poor conditions are illustrated here.

III. Channel Bottom

Water flows over the channel bottom nearly all of the time in perennial streams. It is, therefore, almost totally an aquatic environment, composed of inorganic rock constituents found in an infinite variety of kinds, shapes, and sizes. It is also a complex biological community of plant and animal life. This latter component is more difficult to discern and may in fact, at times and places, be totally lacking.

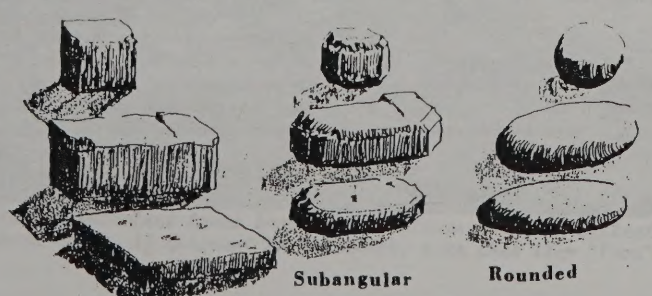
Both components, by their appearance alone and in combination, offer clues to the stability of the stream bottom. They are arbitrarily separated and individually rated for convenience and emphasis during the evaluation process. Because of the high reliance on the visual sense, inventory work is best accomplished during the low flow season and when the water is free of suspended or dissolved substances. If ratings must be made in high flow periods, sounds of movement may be the only clue as to the state of flux on the bottom.

10

A. <u>Angularity</u>: Rocks from stratified, metamorphic formations break out and work their way into channels as angular fragments that resist tumbling. Their sharp corners and edges wear and are rounded in time, but they resist the tumbling motion. These angular rocks pack together well and may orient themselves like shingles (imbricated). In this configuration they are resistant to detachment.

In contrast, igneous rocks often produce fragments that round up quickly, pack poorly and are easily detached and moved downstream.

<u>Excellent</u> to <u>Poor</u> ratings relate to the amount of rounding exhibited and, secondarily, the smoothness or polish the surfaces have achieved. Some rocks never do smooth up in the natural environment, but most round up in time. Both conditions, of course, are relative within the inherent capability of the respective rock types.



Angular   Subangular   Rounded

11

B. <u>Brightness</u>: Rocks in motion "gather no moss", algae or stain either. They become polished by frequent tumbling and, as a general rule, appear brighter in their chroma values than similar rocks which have remained stationary. The degree of staining and vegetative growths relate also to water temperature, seasons, nutrient levels, etc. In some areas a "bright" rock will be "dulled" in a matter of weeks or months. In another it may take years to achieve the same results. Nevertheless, even slight changes during the spring runoff should be detectable during the next summer's survey. Look first for changes in the sands and gravels.

1. <u>Excellent</u>: Less than 5% of the total bottom should be bright, newly polished and exposed surfaces. Most will be covered by growths or a film of organic stain. Stains may also be from minerals dissolved in the water.

2. <u>Good</u>: 5 to 35% of the bottom appears brighter, some of which may be on the larger rock sizes.

3. <u>Fair</u>: About a 50-50 mixture of bright and dull with a 15% leeway in either direction (i.e., a range of from 35 to 65% bright materials).

4. <u>Poor</u>: Bright, freshly exposed rock surfaces predominate with two-thirds or more of the bottom materials in motion recently.

Dull

Mostly Bright

12

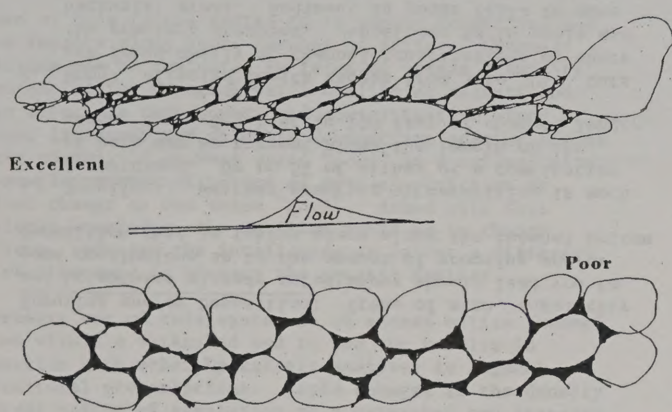
C. Consolidation (Particle Packing): Under stable conditions, the array of rock and soil particle sizes pack together. Voids are filled. Larger components tend to overlap like shingles (imbricate). So arranged, the bottom is quite resistent to even exceptional flow forces. Some rock types (granitics) are less amenable to this packing process and never reach the stable state of others like the Belt Series rocks.

1. Excellent: An array of sizes are tightly packed and wedged with much overlapping which makes it difficult to dislodge by kicking.

2. Good: Moderately tight packing of particles with fast water parts of the cross section protected by overlapping rocks. These might be dislodged by higher than average flow conditions, however.

3. Fair: Moderately loose without any pattern of overlapping. Most elements might be moved by average high flow conditions.

4. Poor: Rocks in loose array, moved easily by less than high flow conditions and move underfoot while walking across the bottom. The shape of these rocks tends to be predominantly round and sorted so that most are of similar size.



Side Views of Substrate

13

D. Bottom Size Distribution and Percent Stable Materials:

Rocks remaining on a stream's bottom reflect the geologic sources within the basin and the flow forces of the past. Normally, there is an array of sizes that you expect to see in any given local. After a little experience, you begin to "sense" abnormal situations. Generally, in the mature topography typical of the Northern Region of the Forest Service and much of the other western Regions as well, the flow in the small, steep upper stream reaches is sufficient to wash the soil separates and some of the gravels away. What remains is a gravelly, cobbly stream bottom. In the lower reaches where the gradient is less and flow is often slower, deposition of the "fines" eroded above begin to drop out. The separates of sand, silt, and some clay begin to cover the coarser elements. Except where trapped in still water areas, these fines tend to be in constant motion to ever lower elevations.

Two elements of bottom stability are rated in this item: (1) Changes or shifts from the natural variation of component size classes and (2) the percentage of all components which are judged to be stable materials. Bedrock, large boulders, and cobble stones ranging in size from one to three feet or more in diameter are considered "stable" elements in the average situation. Obviously, smaller rocks in smaller channels might also be classed as stable. The sizes are given only to guide thought. Bedrock as a major component of bottom and banks, no matter what size the channel or how the other elements rate, always results in an excellent classification of that reach.

1. Excellent: There is no noticeable change in size distribution. The rock mixture appears to be normal for the kind of geologic sources in the basin and the flow forces of streams of this size and location in the watershed.

   If a shift or change has taken place so there are greater percentages of large rock in the small streams and smaller sizes in large streams, the condition class most appropriate should be checked. It is a matter of degree as follows:

   (Stable Materials 80-100%).

2. Good: Slight shift in either direction.

   (Stable Materials 50-80%).

3. Fair: Moderate shift in size classes.

   (Stable Materials 20-50%).

4. Poor: Marked, a pronounced shift.

   (Stable Materials less than 20%).

14

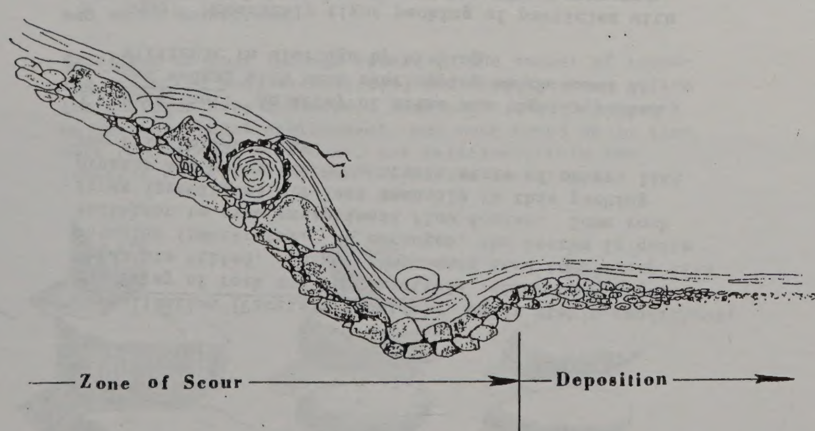
E. Scouring and/or Deposition: Items of size, angularity and brightness already rated above should lead you to some conclusions as to the amount of scouring and/or deposition that is taking place along the channel bottom.

1. Excellent: Neither scouring nor deposition is much in evidence. Up to 5% of either or a combination of both may be present along the length of the reach; i.e., 0-5 feet in 100 feet of channel length.

2. Good: Affected length ranges from 5 to 30%. Cuts are found mostly at channel constrictions or where the gradient steepens. Deposition is in pools and backwater areas. Sediment in pools tends to move on through so pools change only slightly in depth but greatly in composition of their size classes.

3. Fair: Moderate changes are occurring. 30 to 50% of the bottom is in a state of flux. Cutting is taking place below obstructions, at constrictions and on steep grades. Deposits in pools now tend to fill the pool and decrease their size.

4. Poor: Both cutting and deposition are common; 50% plus of the bottom is moving not only during high flow periods but at most seasons of the year.



15

F. Aquatic Vegetation: When some measure of stabilization of the soil-rock components is achieved, the channel bottom becomes fit habitat for plant and animal life. This process begins in the slack water areas and eventually may include the swift water portions of the stream cross section. With a change in volume of flow and/or sedimentation rates, there may also be a temporary loss of the living elements in the aquatic environment. This last item attempts to assess the one macro-aquatic biomass indicator found to best express a change in channel stability.

Clinging Moss and Algae: These lower plant forms do not have roots but cling to the substrate. They are low growing and may first appear as a green to yellow-green slick spot on the bottom rocks. Moss plants continue with slight variation in color but no great change in mass form season to season. Algae by contrast have a peak of growth activity and then die off in great numbers. The slippery conditions they produce persist after death, however.

Both algae and moss inhabit the swift water areas as well as the quiet pools and backwater portions of the stream bottom.

1. Excellent: Clinging plants are abundant throughout the reach from bank to bank. A continuous mat of vegetation is not required but moss and/or algae are readily seen in all directions across the stream.

2. Good: Plants are quite common in the slower portions of the reach but thin out or are absent in the swift flowing portions of the stream.

3. Fair: Plants are found but their occurrence is spotty. They are almost totally absent from rocks in the swifter portions of the reach and may also be absent in some of the slow and still water areas.

4. Poor: Clinging plants are rarely found anywhere in the reach. (This is an unusual situation but could happen under a combination of adverse environmental conditions).

Channels with this much moss are rated "Excellent"

Management Implications

After beating the brush, getting your feet wet and fighting insects, you have established a series of channel ratings. You may now ask, "What do these numbers mean and how are they used in making a management decision?".

By now you know this subject is complicated and precludes indepth answers here. The following brief answers may satsify you or they may raise more questions. When this happens, it's time to consult your Forest hydrologist for detailed, specific answers.

The numbers and the adjective ratings they relate to mean what they say. A stream channel reach that rates "poor" has a combination of attributes that will require more judicious upstream management of the tributary watershed lands than one rated "excellent". This rating procedure was not designed to fix blame for poor land and water management or to reward good management, although, in time, it could be used for this purpose. Before passing judgment, be aware that natural, undistrubed watersheds may exhibit poor hydologic conditions. Conversely, a highly developed and used watershed may have a drainage network in good hydologic shape. The rating system will therefore have the most value to land managers who have definite water management goals, who can relate these to impacts of other resource uses and activities, who understand natural limitations, and who are willing and able to use the system to define the risks they are willing to take to maintain or alter the status quo.

One use of this rating system is to assess conditions and define impacts along short reaches of stream. Channel conditions can be evaluated in terms of stream stability and potential for damaging water quality at culvert and bridge sites, at campgrounds and administrative sites or wherever livestock and wildlife concentrate near or across a water course. A channel rated "poor" at a culvert site, for example, cannot withstand as much constriction or gradient change as one rated "good". Armed with this additional knowledge, the decision could be to change locations, redesign the intallation or select a different type of structure to protect the aquatic habitat.

The primary use of this system is to assess entire channel systems within a watershed and to use the results in conjunction with other hydrologic analyses to augment silvicultural prescriptions. Rapid changes in the density and areal extent of vegetation on a watershed can increase stream discharges. Channel systems rated "excellent" can withstand these increases with less damage than systems rated "poor". "Poor" systems can withstand gradual changes better than abrupt changes in the discharge regimen.

To calculate an overall rating for a stream system, (1) multiply the length of each reach by its numeric rating, (2) add the weighted products of all reaches in the system and (3) divide by the total length of the system.

For example:

Reach A	:	3.2 miles x 80 (fair)	= 256
Reach B	:	0.5 miles x 100 (poor)	= 50
Reach C	:	2.0 miles x 40 (good)	= 80
Total	:	5.7 miles	386

Stream system average: 386 ÷ 5.7 = 68 (Good)

Land and water should not be managed on the basis of averages. In the above example, the stream system is composed of three reaches which rate "good" on the average, but a "weak link" has been identified. Reach B is in "poor" condition. One of the obvious uses of this system is to identify "weak links" and to discover what, if any, opportunity exists to correct the condition. It matters little if the damaged area is natural or man-caused. The discovery of "weak links" should reasonably alter upstream land management to the extent necessary to achieve stated land and water management objectives.

The procedures should ultimately serve as a check and a measure of management success. The net effects of each new increment of change within the watershed management unit will ultimately be expressed in the condition of the stream channel responding to a new hydraulic regimen. Prudent managers will seek these trend data by periodic reappraisal of channel conditions and respond to adverse changes before impacts to the water resource become unacceptable and unalterable.

This large stream channel reach would be rated "excellent" overall.

R-1 STREAM REACH INVENTORY and CHANNEL STABILITY EVALUATION

REACH LOCATION: Survey Date_______ Time______ Obs._________________________

Forest______________________________ Rgr. Dist.____________________________

P.W.I.

Stream______________________________ W/S No. ___-___-___-___-___-___-___-___

Reach Description &

Other Identification____

	Key #	Stability Indicators by Classes (Fair and Poor on reverse side) EXCELLENT		GOOD	
Upper Banks	1	Bank slope gradient <30%.	(2)	Bank slope gradient 30-40%.	(4)
	2	No evidence of past or any potential for future mass wasting into channel.	(3)	Infrequent and/or very small. Mostly healed over. Low future potential.	(6)
	3	Essentially absent from immediate channel area.	(2)	Present but mostly small twigs and limbs.	(4)
	4	90%+ plant density. Vigor and variety suggests a deep, dense, soil binding, root mass.	(3)	70-90% density. Fewer plant species or lower vigor suggests a less dense or deep root mass.	(6)
Lower Banks	5	Ample for present plus some increases. Peak flows contained. W/D ratio <7.	(1)	Adequate. Overbank flows rare. Width to Depth (W/D) ratio 8 to 15.	(2)
	6	65%+ with large, angular boulders 12"+ numerous.	(2)	40 to 65%, mostly small boulders to cobbles 6-12".	(4)
	7	Rocks and old logs firmly embedded. Flow pattern without cutting or deposition. Pools and riffles stable.	(2)	Some present, causing erosive cross currents and minor pool filling. Obstructions and deflectors newer and less firm.	(4)
	8	Little or none evident. Infrequent raw banks less than 6" high generally.	(4)	Some, intermittently at outcurves and constrictions. Raw banks may be up to 12".	(8)
	9	Little or no enlargement of channel or point bars.	(4)	Some new increase in bar formation, mostly from coarse gravels.	(8)
Bottom	10	Sharp edges and corners, plane surfaces roughened.	(1)	Rounded corners and edges, surfaces smooth and flat.	(2)
	11	Surfaces dull, darkened, or stained. Gen. not "bright".	(1)	Mostly dull, but may have up to 35% bright surfaces.	(2)
	12	Assorted sizes tightly packed and/or overlapping.	(2)	Moderately packed with some overlapping.	(4)
	13	No change in sizes evident. Stable materials 80-100%.	(4)	Distribution shift slight. Stable materials 50-80%.	(8)
	14	Less than 5% of the bottom affected by scouring and deposition.	(6)	5-30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	(12)
	15	Abundant. Growth largely moss-like, dark green, perennial. In swift water too.	(1)	Common. Algal forms in low velocity & pool areas. Moss here too and swifter waters.	(2)
		EXCELLENT COLUMN TOTAL →		GOOD COLUMN TOTAL →	

Add values in each column and record in spaces below. Add column scores.

E.___+ G.___+ F.___+ P.___ = _________ Total Reach Score.

Adjective ratings: <38=Excellent, 39-76=Good, 77-114=Fair, 115+=Poor*

*(Scores above may be locally adjusted by Forest Hydrologist)

INVENTORY DATA: (observed or measured on this date)

Stream Width___ft.X Ave.Depth___ft.X Ave.Velocity___f/s=____Flow cfs

Reach Gradient___%, Stream Order___, Turbidity Level _____, Stream Stage______, Sinuosity Ratio ______,

Temperature °F or C of: Air____Water___, Others_______________________________

Key #	Stability Indicators by Classes FAIR		POOR	
1	Bank slope gradient 40-60%.	(6)	Bank slope gradient 60%+.	(8)
2	Moderate frequency & size, with some raw spots eroded by water during high flows.	(9)	Frequent or large, causing sediment nearly yearlong OR imminent danger of same.	(12)
3	Present, volume and size are both increasing.	(6)	Moderate to heavy amounts, predominantly larger sizes.	(8)
4	50-70% density. Lower vigor and still fewer species form a somewhat shallow and discontinuous root mass.	(9)	<50% density plus fewer species & less vigor indicate poor, discontinuous, and shallow root mass.	(12)
5	Barely contains present peaks. Occassional overbank floods. W/D ratio 15 to 25.	(3)	Inadequate. Overbank flows common. W/D ratio > 25.	(4)
6	20 to 40%, with most in the 3-6" diameter class.	(6)	<20% rock fragments of gravel sizes, 1-3" or less.	(8)
7	Moderately frequent, moderately unstable obstructions & deflectors move with high water causing bank cutting and filling of pools.	(6)	Frequent obstructions and deflectors cause bank erosion yearlong. Sediment traps full, channel migration occurring.	(8)
8	Significant. Cuts 12"-24" high. Root mat overhangs and sloughing evident.	(12)	Almost continuous cuts, some over 24" high. Failure of overhangs frequent.	(16)
9	Moderate deposition of new gravel & coarse sand on old and some new bars.	(12)	Extensive deposits of predominantly fine particles. Accelerated bar development.	(16)
10	Corners & edges well rounded in two dimensions.	(3)	Well rounded in all dimensions, surfaces smooth.	(4)
11	Mixture, 50-50% dull and bright, ± 15% ie. 35-65%.	(3)	Predominantely bright, 65%+, exposed or scoured surfaces.	(4)
12	Mostly a loose assortment with no apparent overlap.	(6)	No packing evident. Loose assortment, easily moved.	(8)
13	Moderate change in sizes. Stable materials 20-50%.	(12)	Marked distribution change. Stable materials 0-20%.	(16)
14	30-50% affected. Deposits & scour at obstructions, constrictions, and bends. Some filling of pools.	(18)	More than 50% of the bottom in a state of flux or change nearly yearlong.	(24)
15	Present but spotty, mostly in backwater areas. Seasonal blooms make rocks slick.	(3)	Perennial types scarce or absent. Yellow-green, short term bloom may be present.	(4)
	FAIR COLUMN TOTAL →		POOR COLUMN TOTAL →	

Size Composition of Bottom Materials (Total to 100%)

1. Exposed bedrock..........___%	5. Small rubble, 3"-6".....___%
2. Large boulders, 3'+ Dia....___%	6. Coarse gravel, 1"-3"....___%
3. Small boulders, 1-3'.......___%	7. Fine gravel, 0.1-1".....___%
4. Large rubble, 6"-12".......___%	8. Sand, silt, clay, muck..___%

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INCORPORATING UNCERTAINTY IN THE DESIGN OF STREAM CHANNEL MODIFICATIONS[1]

Peggy A. Johnson and Eric R. Brown[2]

ABSTRACT: The designs of stream channel naturalization, rehabilitation, and restoration projects are inherently fraught with uncertainty. Although a systematic approach to design can be described, the likelihood of success or failure of the design is unknown due to uncertainties within the design and implementation process. In this paper, a method for incorporating uncertainty in decision-making during the design phase is presented that uses a decision analysis method known as Failure Modes and Effects Analysis (FMEA). The approach is applied to a channel rehabilitation project in north-central Pennsylvania. FMEA considers risk in terms of the likelihood of a component failure, the consequences of failure, and the level of difficulty required to detect failure. Ratings developed as part of the FMEA can provide justification for decision making in determining design components that require particular attention to prevent failure of the project and the appropriate compensating actions to be taken.

(KEY TERMS: decision making; hydraulics; stream restoration; design; uncertainty, failure; adaptive management.)

INTRODUCTION

Stream restoration, rehabilitation, and stabilization projects are being planned, designed, and constructed at an increasing rate in locations all across the country. Guidelines for designing these projects are often vague and qualitative in their approach. In many cases, the lack of definitive design procedures has resulted in frustration, excessive costs, and poor results.Engineering design is a systematic process that provides a framework for achieving design objectives. The design process includes the following steps: problem definition, solution creation, analysis of solutions, solution evaluation, problem resolution, and solution implementation.

For stream restoration, this type of systematic approach results in the following set of steps:

1. Define the problem by assessing channel stability and habitat conditions, setting clear and specific objectives for the project, and assessing risks and constraints.

2. Create solutions by determining design alternatives to achieve objectives.

3. Investigate solutions by collecting and analyzing the required data to determine the design loads and parameters.

4. Evaluate the solution by determining possible upstream and downstream impacts for each design and by eliminating alternatives based on risk, constraints, and impacts.

5. Finalize the design based on the best alternative according to the solution evaluation.

6. Implement the solution and develop a monitoring plan.

Although the design process is conceptually straightforward, there are many factors in stream modification designs that complicate this process. Some of these factors include: (1) objectives are often vague and, thus, it is difficult to develop specific solution alternatives that would achieve the objective; (2) interference in the design caused by road crossings

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is quite common, especially in urban and suburban areas; (3) other urban constraints, such as lack of lateral easement and existing infrastructure (e.g., water lines, sewer lines, and culverts), do not permit the design of a naturalized stable channel; (4) each restoration site is unique and the underlying causes of the observed disturbance are often complex and difficult to unravel so that a single set of design guidelines is unable to globally address issues at a given site; (5) river restoration projects are, or should be, highly interdisciplinary, often resulting in communication problems between the disciplines; (6) geomorphic and ecologic responses and time frames for responses to a given design are complex and difficult to predict; and (7) existing problems are often due to multiple causes.

The lack of definitive design guidelines and the complexity of the geomorphic and ecologic system result in a relatively high degree of uncertainty in modifying a stream. Adaptive management was developed as a method to make informed decisions regarding river restoration that embrace uncertainty (Holling, 1978; Walters, 1986). Adaptive management is based on formal experimentation (as opposed to trial-and-error), attention to scientific uncertainties in processes and responses, and experimental design and hypothesis testing to reduce uncertainties (NRC, 1999). In addition, adaptive management uses information gained through careful monitoring of the restoration site to guide future decisions. Thus, a central component of designing and adaptively managing a stream restoration project is acknowledgment of the uncertainty, and thereby risk, in our understanding of the complex system. In this paper the sources of uncertainty and the impact on stream restoration design are described. Methods for incorporating uncertainty are also presented.

SOURCES OF UNCERTAINTY

Adaptive management evolved from the notion that stream restoration is often replete with uncertainty in all phases of the restoration project, including design, implementation, and monitoring. Adaptive management embraces these uncertainties for making decisions during all three phases (Walters, 1986; McLain and Lee, 1996; Thom, 1997; Kershner, 1997). Uncertainty primarily results from our lack of knowledge; it is generally reduced as our knowledge and understanding of complex river processes and responses increase. Uncertainty leads to a risk of failure and so it is critical that it is acknowledged in stream restoration activities.

There are several broad categories of uncertainty that are common to any design process. They include:

- **Model Uncertainty**. This results from attempting to describe a complex physical process or phenomenon through the use of a simplified mathematical expression. Examples of models used in stream restoration designs include regional regression equations, sediment transport equations, and ecological response models.

- **Parameter Uncertainty.** This type of uncertainty results from difficulties in estimating model parameters. For example, Manning's roughness coefficient and dominant discharge are two common stream design parameters that cannot be measured directly; therefore, they must be estimated or assumed. The result is parameter uncertainty.

- **Randomness.** Natural (or inherent) randomness is a source of uncertainty that includes random fluctuation in parameters, such as flow discharges and velocities.

- **Human Error.** There is always potential for human error in design and in the actual implementation of a design. This type of uncertainty includes calculation and construction errors.

In a stream restoration design, there are many individual factors which contribute to each of these categories of uncertainty, thereby decreasing the reliability of the design (Johnson, 1996; Johnson and Rinaldi, 1998). Specific sources of uncertainty are described below.

Ecosystem and Physical System Modeling

Models are used in the stream restoration process for two primary purposes: design and response predictions. Equations and models are used in the design process to quantify any number of parameters, including cross sectional geometry, planform geometry, sediment transport, shear stresses within the channel and on the floodplain, and velocities and flow depths for a range of flow conditions. Response models are used to calculate the physical or ecological response to changes in the physical system, such as the stability of a channel, the long-term sediment transport conditions, and local scour and fill patterns. Regardless of the purpose, all of these models are mathematical representations, and typically simplifications, of complex physical processes and phenomena. Most of the

els are either semi-empirical or completely empirical and, as such, are based on data from specific regions, watersheds, or reaches. Thus, while the models may work well for certain situations or settings, they may work poorly for others. In addition, a full understanding of these complex phenomena has not been achieved. The result is that there are no models that can accurately predict all of the responses to change in the physical system for all settings and conditions. Therefore, varying degrees of uncertainty are associated with the use of these models. Generally speaking, model uncertainty is often the primary source of uncertainty.

Restoration Objectives

Setting objectives for any design is required so that the purpose of the design can be met. In stream restoration projects, the objectives are often vague because of the difficulty in setting specific, measurable objectives. Thus, vague objectives, such as improvement of the aquatic or riparian habitat, physical stability of the stream, or aesthetic qualities of the stream corridor, are often stated as the project objectives. To set more specific objectives than these, the definition of improvement or stability in the physical system and ecosystem must be clearly articulated. For example, a stated objective might be to improve the aquatic habitat. This vague objective does not indicate a measurable goal, such as a specific desired reduction in water temperature, an increase in flow diversity, or an increase in the diversity or number of species. Another common objective is to create a stable channel. In this case, acceptable levels of bank and bed erosion and lateral migration should be clearly stated in terms of a magnitude per year or other quantity, particularly where urban and suburban development is limiting the river's lateral movement. Without specific objectives, the design success in achieving the objectives will be unknown. Clearly defined objectives are also required for meaningful monitoring following the construction of the project site so that monitoring data can be used to assess the success or failure of the project.

Vague Definitions

Tied to the ability to set clear, specific objectives is the problem of defining various terms that describe the ecologic or physical condition of a stream. For example, vague definitions can be given for channel stability, ecologic diversity, and project failure. However, providing specific, measurable definitions such that the response and outcome of the project can be measured and a degree of success can be associated with the level of achievement of these terms is far more difficult. Thus, uncertainty exists because there is an inability to accurately define important terms that are used to assess the state of the stream corridor.

Vague Design Procedures and Guidelines

Rosgen and Fittante (1986) propose that failures of instream habitat improvement projects are due in part to the lack of field experience and documented procedural guidelines for using these methods. Although stream restoration guidelines have been established by several government agencies, they are often rather vague and rarely differentiate between varying physiographic and geologic conditions. Most manuals describe the design process qualitatively or quantitatively or both. However, the causes of the problems in a given stream corridor are numerous and complex and the remedy will vary by geologic and physiographic regions as well as the level of urbanization. Given the uniqueness of each restoration site and the inability to quantify the response of the system to changes, it remains that a well designed restoration project requires field experience as well as design procedures. Thus, there is considerable uncertainty due to an inability to incorporate experiential understanding of complex river systems into the design guidelines.

Parameter Estimation

Parameter uncertainty results from an inability to accurately assess parameters and coefficients required in models. There are a variety of parameters associated with river restoration that are difficult to estimate with certainty. A few examples include the bankfull elevation and width, asymmetric and irregular meander dimensions, and the roughness coefficient or friction factor. Approximate or average values are commonly used for these parameters which may lead to a somewhat inappropriate and uncertain design.

Monitoring

Monitoring is an essential component of any stream restoration project and adaptive management schemes. Data acquired during monitoring are used to determine the degree of success of the restoration

project and to provide input into additional remedies. However, there is considerable uncertainty in the monitoring process. It is unclear how many data, what types of data, and what locations should be monitored following construction of the restoration project. When data are collected, they are analyzed to assess the health and success or failure of the project. Because the objectives are frequently vague, it is difficult to interpret the results of the data analyses in terms of success or failure or the need for further modifications. It is also not readily apparent when and for what hydrologic events monitoring should take place. Should a stream be monitored during a rising/falling hydrograph or after the hydrologic event when the flood waters have receded? Many county and state jurisdictions have policies that require three to five years of post-construction monitoring. The selection of the monitoring duration is somewhat arbitrary, but tends to be the length of time over which streams make their primary adjustments to their new planform, cross-sectional geometry, and in-stream measures. However, there is much disagreement as to the appropriate length of time for monitoring activities. Thus, uncertainty in monitoring protocol yields uncertainty in assessing whether the objectives have been met and in the implementation of further remedies.

Scale

There are several issues related to scale in stream restoration. First, many stream restoration techniques discussed in the literature and in design guidelines are developed for small to moderate streams. The ability to transfer those design practices from one scale to another has not been well established. Therefore, the likelihood of the implementation of these techniques on larger rivers is unknown and fraught with uncertainty.

A second source of uncertainty is related to the scale over which the restoration is performed. Often, restoration efforts cannot be performed over the entire length of the river due to various constraints and limitations. Thus, decisions must be made regarding the locations and extent of restoration sites. The reach lengths and proximity of the disjointed reaches to each other, in part, dictate whether or not the restoration will succeed in creating a self-sustaining, resilient stream channel. However, the optimum reach lengths and spacings are unknown and, thus, contribute to the overall uncertainty.

Climate Change

It is well established that climatic changes are occurring in large areas around the world due to both natural and human-induced activities. The effects of climatic changes can include increases or decreases in air temperature and changes in hydrologic regimes. The effect of such climatic changes on the ability of a stream restoration project to continue to be self-sustaining over a long period of time is unknown. In addition, the direction and magnitude of the change is unknown and is a subject of great debate.

Land Use Changes

Changes in land use within a given watershed often result in a change in the boundary conditions, i.e., the flow and sediment discharges delivered to a river reach. For example, a change from agricultural to urban or suburban may result in an increase in flow discharge and a decrease in sediment discharge. If these changes take place during the restoration design and implementation, the result may be failure or partial failure of the project. In addition, changes in the boundary conditions in the years following the restoration implementation can also result in the eventual failure of the project. It is difficult to include the expected boundary condition changes in the restoration design since the restoration must be primarily designed for current conditions so that it does not experience instability. Thus, uncertainty in future land use changes and uncertainty in the method for incorporating expected land use changes results in uncertainty in the overall design.

Construction and Implementation Practices

There are a number of sources of uncertainty involved in the implementation of a restoration project. An experienced construction crew can markedly improve the likelihood of success of a project. Many problems are encountered in the field that may be overlooked in the design phase which will then require experienced personnel to solve on site. In addition, inadequate supervision of the construction project by the design team can lead to inappropriate decision making on site. Human error in measurement, placement of measures, or excavation can also lead to partial or complete failure of the project. It is always difficult to account for human error in a project design; however, this type of uncertainty can be reduced by assuring that the field crew is experienced

that there is constant communication between the crew and the designer.

INCORPORATING UNCERTAINTY INTO DESIGN

It is not a trivial matter to quantify uncertainty. Methods, such as first-order analyses and Monte Carlo simulation, are frequently used to compute uncertainty. For these methods, a mathematical model, coefficients of variation, probability distributions, and joint probability distributions are required. Many of the sources of uncertainty described above are not readily quantifiable and cannot be directly incorporated into a model predicting system response. In addition, models are not available for many aspects of stream restoration, such as the quantification of channel response to a disturbance. Qualitative models may exist, but it is difficult to associate a quantitative value to these models.

An alternative to the direct calculation of uncertainty is to include it in the decision-making process. Incorporating uncertainty into decisions regarding stream restoration design, implementation, and monitoring is a key component of adaptive management. Embracing uncertainty allows the restoration practitioner to incorporate or at least consider multiple causes of existing problems or to consider multiple hypotheses. It may also help to reduce the costs of restoration projects in that the projects will be less likely to have to be redesigned or reconstructed if multiple hypotheses are considered initially.

There are a number of methods available for qualitatively, semi-quantitatively, or quantitatively assessing the causes and effects of a wide variety of factors in uncertain, complex systems and for making decisions in light of uncertainty. These methods, including fault tree analysis, decision trees, and failure modes and effects analysis (FMEA), are based on analyses of failures. A potential failure can be affiliated with a failure cause, a failure mode, and a failure effect, although these are sometimes very unclear and difficult to define in real-life situations (Rao, 1993). A failure mode is the manner in which a system or system component may fail to meet design intent (Bluvband and Zilberberg, 1998). For a failure mode analysis of any type, it is of paramount importance to first define what constitutes a system failure (Krasich, 2000).

In the context of river and stream modification design, failure modes may bring about functional or structural failures, thereby jeopardizing project goals and objectives. A structural failure is identified as a collapse of the physical system or components of the system sufficient to prevent fulfillment of the design objectives. A functional failure implies that the project objectives cannot be realized due to the ineffectiveness of the design, although the structure or form may be intact and in place. Since the fulfillment of structural objectives is a prerequisite to other restoration and stabilization targets, the occurrence of structural failures will be the focus of this paper.

Fault Tree Analysis

Many failure phenomena can be systematized as a chain or hierarchy of events, thereby linking causes of some events to the effects of others (Rao, 1993). Ultimately, a detailed hierarchy of contributing events to the top-level system failure event can be established. A fault tree is a diagrammatic representation of these relationships among component-level failures and system-level undesired events. Fault tree analysis is a structured procedure used to graphically define the hierarchical relationships among a system failure and component failure modes. A fault tree can assist in the identification of paths to failure and can be used to single out critical events. Fault trees also can be used to assess the probability of failure for the system (or top event), to compare design alternatives, to identify critical events that will significantly contribute to the occurrence of the top event, and to determine the sensitivity of the probability of failure of the top event to various contributions of basic events. Fault tree analysis has been implemented to model a variety of engineering applications including the causes of construction falls (Hadipriono, 1992), bridge failures resulting from scour and stream instability (Johnson, 1999), failure of urban infrastructure following stream restoration (Hess and Johnson, 2001) and the failure of coastal flood protection measures (Vrijling, 1993).

Fault tree analyses can be either qualitative or quantitative, depending on the desired output. Qualitative analyses provide information about the importance of the basic events. Cut sets are commonly used for this type of analysis. A cut set is a combination of terminal events that is sufficient to cause an occurrence of the top event (Sundararajan, 1991; Ayyub and McCuen, 1997). In other words, if all terminal events in a cut set occur, then the top event will occur. A minimal cut set is defined as the smallest subset that is sufficient and necessary to cause the occurrence of the top event. In a quantitative fault tree analysis, the top event is related to subevents and basic faults through gates representing mathematical operations for combining the probabilities of those events. The calculation of the probability of occurrence of the top event is is a function of the probabilities of the basic events and the type of gate. If all

events in a fault tree are independent, then the calculations are straightforward. However, if some of the events are dependent, then information regarding the conditional probabilities is required.

There are several drawbacks to the use of fault tree analysis for complex systems, such as a river system. First, a quantitative analysis requires probabilities of occurrences for all events contributing to failure as well as conditional probabilities for dependent variables. These are rarely known in river systems. Second, for very complex systems that require large fault trees, it is possible to overlook or miss failure modes (Sundararajan, 1991). In this case, the probability of occurrence of the top event or other events could be nonconservative. Third, there are only two possibilities of the occurrence of any event; the event either occurs or it does not. Fuzzy or changing failure modes cannot be readily accounted for.

Decision Trees

Decision trees, commonly used in engineering and management applications to evaluate and reduce risk, are ideally suited to choosing an optimal alternative or option for a system design or problem. Used in this context, alternatives refer to choices or decisions and should not be confused with physical system components such as bank stabilization alternatives. To achieve this goal, decision trees can be used to effectively evaluate the consequences of a sequence of decisions (i.e., list of feasible alternatives or options) by calculating corresponding probability assignments and resulting utility values to be used for the purpose of comparison (Ang and Tang, 1984). Ultimately, the decision as to which alternative is superior depends on the relative utility values calculated for all potential outcomes.

One of the drawbacks of decision tree analysis is that probabilities are required for each alternative and outcome. As with fault tree analysis, these probabilities are rarely known. In addition, the calculation of a utility value requires the costs associated with each alternative and outcome.

Failure Modes and Effects Analysis (FMEA)

FMEA is a qualitative procedure to systematically identify potential component failure modes and assess the effects of associated failures on the operational status of the system (Dushnisky and Vick, 1996). FMEA is performed prior to design implementation so that the risk of component or system failure can be assessed and changes to the design implemented at low relative cost. The following are required to execute a FMEA (McCollin, 1999):

- a hierarchical structure for the system illustrating all system components,
- failure modes of all components of the system, and
- an objective criterion for implementing corrective action (the most commonly used is the risk priority number).

Due to the hierarchical nature of composite systems, failure modes exist at differing levels of detail or scale; therefore, analysis of the system starts with failure at the lowest level of scope and describes how the next higher level is affected.

In the past, FMEA has been used to advance the understanding of complex electrical and mechanical systems including numerous applications in nuclear safety (e.g., McCormick, 1981; American Nuclear Society, 1983; Fullwood and Hall, 1988; Henley and Kumamoto, 1992; Shimizu *et al.,* 1993) and to evaluate and rank potential problems in manufacturing processes. Formulation of the FMEA begins with identification of the system and all of its components (Dushnisky and Vick, 1996). Next, the range of possible failure modes is defined as mutually exclusive collectively exhaustive events. Basic sources of failure modes typically include documented case studies, laboratory experimentation, field experience, and expert opinion. Once the failure modes are identified for each component of the system, their effects on the system and other system components, consequences, likelihoods of occurrence, methods of detection, and compensating provisions (i.e., possible corrective actions) are listed. The system designer arbitrarily chooses numeric ratings (e.g., 1 through 10) for these criteria, with the largest values associated with the most severe consequence level and the highest likelihood of occurrence. By using ratings for consequences and occurrences, in addition to a rating for detectability (likelihood that the failure mode will be observed), failure modes can be prioritized to focus a greater level of effort on higher priority failures.

The most common method of establishing prioritization among failure modes is through the implementation of risk priority numbers. A risk priority number (RPN) is a characteristic quantitative result from a FMEA used to suggest the appropriate nature and extent of corrective actions for failures at all levels of system scope. The RPN is the product of the occurrence, consequence, and detectability ratings of a given failure mode, although other factors may be included in an advanced FMEA, such as associated cost and required resources to implement corrective actions (Bluvband and Zilberberg, 1998). Even though

ratings are somewhat arbitrary labels rather than numbers representing explicit numeric quantities, the relative values can be compared and used to prioritize failures. Failure modes having a high relative RPN (i.e., a high risk) are assumed to have a larger impact on system failure than those with a lower RPN.

Use of the risk priority number can be highly subjective if the criteria for determining its value and its implication toward corrective adjustments are not adequately defined prior to conducting the FMEA. Numerical values for consequence level, occurrence frequency, and detectability need to be established as a preliminary step to any analysis. Associating degrees of corrective action with ranges of RPNs prior to analysis requires establishing numeric values for thresholds and cutoff points to define these ranges.

EXAMPLE OF INCORPORATING UNCERTAINTY INTO CHANNEL MODIFICATION DESIGN

The Bentley Creek watershed is located in the north central portion of the Susquehanna River basin, comprising the northwestern section of Bradford County, Pennsylvania, and the southeastern section of Chemung County, New York. Three key problems were identified at the Bentley Creek site dating back to the occurrence of Hurricane Agnes in 1972: (1) streambank erosion, resulting in large property losses and endangerment of homes and businesses located near the stream channel; (2) increased sedimentation resulting in aquatic habitat destruction and blockage of bridge openings; and (3) heightened flood stages from partial reduction in channel capacity (U.S. Department of Agriculture, 1997).

A 1997 survey of the extent of Bentley Creek by the Natural Resources Conservation Service (U.S. Department of Agriculture, 1997) identified 78 percent (33,465 feet) of the main stem of Bentley Creek as having unstable banks. Some practices aggravating the situation included inappropriate and inadequate channel modification and stabilization efforts, insufficient bridge openings, lack of adequate riparian vegetation (resulting from Hurricane Agnes and subsequent efforts to clear debris from the channel with heavy machinery), debris blockages, and development in the stream's riparian zone.

In November 1998, a decision was made to modify Bentley Creek in an effort to:

- reduce or eliminate flood damages to Wellsburg, New York, and Ridgebury Township, Pennsylvania;
- arrest the deposition of sediment blocking stream channels and bridge openings; and
- significantly reduce streambank erosion to protect life and property.

One mile of the main stem of Bentley Creek was to be reconfigured with the addition of three meander bends and a modified cross sectional geometry to help decrease flow velocity and constructed with an enlarged floodplain to decrease flood flow energy. Instream measures were to include single-wing vanes, cross vanes, and root wads to fulfill local stability objectives including flow redirection and grade control.

FMEA is used here to illustrate a relatively simple technique to incorporate uncertainty into the design process for the Bentley Creek project. The basic setup for the FMEA is given in Table 1. Column 1 provides the components of the project, which include local measures (vanes, cross vanes, and root wads) as well as modifications to the channel itself (change in the cross sectional geometry, localized channel relocation, and meander construction). The local measures are used for bank stabilization and to direct the flow away from road embankments. The cross section was to be changed to contain the estimated dominant flow. Downstream of one of the bridges, the channel was to be moved so that the angle at which it met a tributary was reduced. Meanders were to be constructed to approximate the sinuosity that existed prior to channel straightening. In Column 2, the failure modes for each component are given based on experience, prior failures at other sites, and knowledge of channel adjustments. Columns 3 and 4 describe the anticipated local and system-wide effects, respectively, of the stated failure mode associated with a specific component. Column 5 describes methods for detecting failure based on field experience and documented case studies. Column 6 gives compensating provisions, or possible corrective actions, should failure occur. Columns 1 through 6 must be established prior to calculating RPNs and prior to taking action to reduce uncertainty.

The calculation of RPNs requires that consequence, occurrence, and detectability ratings are first established. Tables 2 through 4 were developed to provide these ratings for this example. As stated previously, the rating scales given in these tables are chosen arbitrarily. In this case, the various factors are given ratings of 1 through 10. The failure or partial failure of a stream restoration project has impacts both economically and environmentally, particularly in terms of available habitat. In addition, public scrutiny of the project can have an enormous impact on future projects. Thus, Table 2 reflects these three outcomes categorized into four levels of consequences. Table 3 is primarily based on prior experience using these types of designs as well as characteristics of Bentley Creek

TABLE 1. FMEA Example for Design of Bentley Creek Project.

Components (1)	Failure Mode (2)	Effects on Other Components (3)	Effects on Whole System (4)	Detection Methods (5)	Compensating Provisions (6)
Vanes and Cross Vanes	Burial by incoming sediment	None or minimal	Minimal	• Measure has a lower profile	• Re-orient or reposition measure
	Rapid lateral migration away from vane from vane	None or minimal	May cause property or infrastructure damage	• Bank retreat at bank pins • Proximity to structures and/or survey marker	• Armor opposite bank • Construct vanes on opposite bank upstream to direct flow toward vane
	Erosion of opposite bank	Erosion around measures	Minimal, some sediment input	• Bank retreat at pins • Raw banks • Undercutting of bank	• Re-orient or reposition measure
	Ineffective angles	Minimal, nearby measures may be less effective	Minimal, may cause design to be less effective	• Scoured pool position incorrect • Scour around bankside of vane	• Re-orient or reposition measure
Rootwads	Excessive scouring	Additional erosion at d/s measures	Rapid bank erosion following failure; sediment input	• Scalloped banks between wads • Root wad popped out	• Add additional rootwads • Use alternative measures
Cross Sectional Geometry Change	Rapid widening	Failure of adjacent measures	Sediment input; local to regional property or structural loss	• Rapid bank retreat at bank pins • Increased channel width • Geotechnical failure planes	• Alter bank side slopes • Add vanes and/or cross vanes • Armor banks • Adjust channel
	Excessive deposition (too wide)	Burial of other measures	Increased flooding	• Measures have lowered profile • Bed elevation increase • Decrease in longitudinal slope	• Decrease channel width • Install vanes and/or cross vanes
	Bed Degradation (too narrow)	Undermining of measures	Eventual bank collapse, loss of overbank habitat	• Bed elevation decrease • Undermining of measures • Headcuts	• Widen channel • Install weirs or check dams • Install deflectors to encourage bank widening
Channel Relocation Downstream of Bridge	Channel migration	Burial of other measures; undermining of other measures	Loss of property	• Bank retreat at bank pins • proximity to structures and/or survey marker	• Install vanes on migrating side • Armor banks
	Excessive deposition d/s of bridge	Minimal	Loss of conveyance at bridge, increased flooding	• Bar formation • narrowing of channel	• Install vanes and/or cross vanes; narrow and/or straighten channel

TABLE 1. FMEA Example for Design of Bentley Creek Project (continued).

Components (1)	Failure Mode (2)	Effects on Other Components (3)	Effects on Whole System (4)	Detection Methods (5)	Compensating Provisions (6)
Meander Construction	Rapid lateral or downstream meander migration	Burial of other measures; undermining of other measures	Loss of property; failure to convey Q and Q_s*	• Bank retreat at bank pins • Proximity to structures and/or survey marker	• Install vanes on migrating side • Armor banks
	Excessive deposition	Burial of other measures	Increased flooding	• Measures have lowered profile • Bed elevation increase • Decrease in longitudinal slope	• Install vanes and/or cross vanes • Narrow and/or decrease sinuosity

*Q_s is the sediment discharge (load entering restoration reach). Qs can be decreased at either the watershed or reach level, depending on the source of the material. At the watershed level, steps must be taken to decrease sediment input into the stream. At reach level, steps must be taken upstream of the project reach to reduce bank widening and/or bed degradation.

TABLE 2. Consequence of Categories.

Consequence Category	Loss of Life	Outcomes of Failure: Economic Impact	Aquatic Habitat Impact	Public Scrutiny	Rating
I (Low)	None	• Minimal replacement cost relative to project budget • Susceptibility to failure of other measures is not increased • No or minor impacts to public and/or private property	No or minor short-term negative impacts in localized areas	Low	1
II (Marginal)	None	• Moderate replacement cost relative to project budget • Replacement of supporting or integrated enhancement measures required • slight to moderate public and/or private property damage (e.g., minor roadway embankments compromised)	Moderate short-term negative impacts in localized areas	Moderate	4
III (High)	None	• Moderate to high replacement cost relative to project budget • Replacement of a significant portion of the project • Failure of minor infrastructure, moderate to high public or private property damage	Not used to identify high impact levels	High	7
IV (Critical)	Possible	• High replacement cost relative to project budget • Replacement of a significant portion of the project • Failure of hydraulic or engineering infrastructure; loss of service provided by infrastructure and/or public utilities; high public or private property damage	Not used to identify critical impact levels	High	10

prior to project implementation. The categories and ratings in Table 4 were based on the level of difficulty to detect channel adjustments, ranging from visual observations to installation of equipment, such as scour chains or pressure transducers.

For each component and failure mode, ratings were assigned for consequence, occurrence, and detectability. These are given in Table 5. The RPNs were calculated as the product of the three ratings. As shown in Table 5, rapid channel widening and

TABLE 3. Occurrence Likelihood.

Occurrence Likelihood	Rating
Impossible or has never occurred previously	2
Remotely possible; similar events may have occurred previously	4
Possible; has previously occurred rarely	6
Probable; has previously occurred occasionally	8
Reasonably probable; has previously occurred frequently	10

TABLE 4. Detection Rating.

Detection Methods	Rating
Simple visual from field inspection	1
Simple analysis from photo record, bank pins	4
Cross sectional or longitudinal surveys; pebble counts; sediment sampling	7
Scour chains, pressure transducers, on other in-situ installations required	10

TABLE 5. Risk Priority Numbers for Bentley Creek Restoration Project.

Component	Failure Mode	Consequence Rating	Occurrence Rating	Detection Rating	Risk Priority Number
Vanes and Cross Vanes	Burial by incoming sediment	1	6	1	6
	Rapid lateral migration away from vane	1	4	4	16
	Erosion of opposite bank	4	6	1	24
	Ineffective angles	1	4	1	4
Rootwads	Excessive scouring	4	8	1	32
Cross Sectional Geometry Change	Rapid widening	4	8	4	128
	Deposition	4	8	4	128
	Degradation	4	4	7	112
Channel Relocation	Channel migration	4	4	4	64
	Excessive deposition d/s of bridge	7	4	1	28
Meander Construction	Rapid meander migration	7	4	4	112
	Excessive deposition	4	10	1	40

sediment deposition due to the change in cross sectional geometry received the highest RPNs. As the channel widens (due to bank failure), significant amounts of sediment can be added to the flow, similar to the problem in this stream prior to restoration. The sediment is then deposited downstream, typically at an over-widened cross section, a meander or bridge, and causes an increase in flooding as well as loss of property as channel widening removes bank material from private property. Thus, the greatest emphasis should be placed on developing a cross sectional geometry that can efficiently convey the sediment and water load, yet not produce shear stresses that will cause bank erosion. Local measures, such as vanes, can be used to assist in this effort. Based on the low RPNs for these in-stream structures, provided that the cross sectional geometry is appropriate, failure of a vane will not produce a high level of risk for the project. Degradation due to the change in cross sectional geometry and rapid meander migration due to meander construction also received relatively high RPNs. Thus, particular attention should be paid to

ability of the channel to convey its load and to proper armoring of bends, particularly at bridges and other sensitive locations.

CONCLUSIONS

Uncertainty is an important aspect of stream restoration and other channel modifications. Adaptive management has been used in a variety of ways in an attempt to address and incorporate uncertainty in design, implementation, and monitoring. To assist in this effort, it is desirable to have a simplified technique for incorporating uncertainty into the decision making process during the design and post-construction monitoring of a restoration or other modification project. Failure modes and effects analysis (FMEA) was used here to demonstrate a relatively simple technique for assigning relative ratings to all components at the design phase. The ratings can then be used to determine components of the design that require particular attention to prevent failure of the project. This information yields the appropriate compensating actions to be taken and provides justification for decision making. FMEA is an appealing method because it considers risk in terms of the consequences of failure, the likelihood of a component failure, and the level of difficulty required to detect failure.

The method demonstrated here for incorporating uncertainty is a decision tool based on a given design. It does not address whether a project will be successful in meeting the project objectives. For example, the objective of the Bentley Creek project was to alleviate downstream aggradation and and reduce property loss due to bank erosion. The use of FMEA could not evaluate whether these objectives would be met.

The Bentley Creek example provided a demonstration of incorporating uncertainty into the design phase of the project. With a "design-not-to-fail" philosophy, FMEA is implemented to determine failure modes and remove their causes before the design is implemented (McCollin, 1999). Thus, the preventative action in the FMEA implies modification of the system design for risk reduction before the design is in place. A slight modification of this technique referred to as Failure Modes, Effects, and Criticality Analysis (FMECA), can also be used in a similar way for monitoring in the post-construction phase. As with FMEA, FMECA is used to evaluate the importance of failure effects on a system's performance (Shimizu *et al.*, 1993). The main point of note is the FMECA provides a basis for carrying out appropriate corrective action once failure has occurred while there is time for these actions to have significant impact on a proper system performance (McCollin, 1999). Apart from a few subtle points of difference in terminology, FMECA is applied in the same manner as FMEA.

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Problem Sets

IN-CLASS PROBLEM #1
Building a Periodicity Chart and Habitat Matrix
BLM Training Course No. 7000-12

The Problem:

Periodicity charts and habitat matrices are commonly used in the aquatic habitat restoration field to summarize life history and habitat information for target fish species. These tools are especially useful when the investigator has little prior knowledge of the species or there are numerous species under consideration.

For this exercise, please do the following:

1. Review pages 1 to 7 in the Cutthroat Trout Habitat Suitability Index Model publication.

2. Using the attached form, build a periodicity table for the species. If you have management experience with the species, feel free to base your responses on that more site-specific information. If not, generalize.

3. Using the attached form for guilding criteria, complete the habitat matrix for cutthroat trout.

4. Compare your cutthroat habitat matrix with those on the handout discussed in lecture. Which species does the cutthroat most closely resemble? Note: If you miss this one, there will be no recess!!!

PERIODICITY CHART

Species: Cutthroat Trout   System: Southwest River

Microhabitat Usage	J	F	M	A	M	J	J	A	S	O	N	D
Adults												
Summer resting												
Winter Resting												
Spawning												
Incubation												
Fry/Larvae												
Juvenile												
Feeding												
Aquatic source												
Adult												
Juvenile												
Fry												
Terrestrial source												
Adult												
Juvenile												
Fry												

	Riverine						Lacustrine																						
	Habitat			Stream size			Habitat					Cover					Temperature[a]			Spawning[b]							Turbidity tolerance		
							Near-shore		Open-water																				
Species	Riffles, runs	Pools, eddies	Backwaters, bayous, oxbow lakes	Small (< 5 m); order: 1-3	Medium (5-30 m); order: 2-6	Large (>30 m); order: 5+	Shallow (≤ 5 m)	Deep (> 5 m)	Surface (< 5 m)	Mid-water (5-15 m)	Deep (> 15 m)	Rocky substrate	Aquatic vegetation	Cut-banks	Logs, brush, debris piles	No special cover needs	Cold (< 20°C)	Cool (20-28°C)	Warm (> 28°C)	Free-drifting eggs, no substrate req.	Eggs deposited in or on rocky substrates; current required	Eggs deposited in or on rocky substrates; no current required	Eggs deposited on plants	Eggs deposited in holes, cavities	Eggs deposited in nests of mud, sand, or plant debris	Eggs deposited over a variety of substrates	Low (< 25 JTU)	Moderate (25-100 JTU)	High (> 100 JTU)

[a] Categories from Hokanson (1977)

[b] Categories from Balon (1975)

Guilding criteria for freshwater fishes.

IN-CLASS PROBLEM #2
Slide Quiz Identifying Habitat Features
BLM Training Course No. 7000-12

Instructions:
You will be shown 10 photographs of streams and asked to name the identified habitat feature. Circle only one answer per question.

1. Name this mesohabitat: A. Riffle B. Step pool C. Dammed pool D. Cascade

2. According to Rosgen's classification, this channel type is an: A B C D E F G

3. This habitat feature is a: A. Glide B. Cut-off meander C. Braided channel D. Pool

4. This type of ice is: A. Anchor B. Shelf C. Frazil D. Cube

5. Name this mesohabitat: A. Mid-channel pool B. Lateral scour pool C. Cascade D. High gradient riffle E. Low gradient riffle

6. Name this mesohabitat: A. Backwater eddy B. Low gradient riffle C. Cut-off meander D. Braided channel E. Glide

7. Name this mesohabitat: A. Low gradient riffle B. Cascade C. Waterfall D. Run

8. A pool formed here would be a: A. Lateral scour pool B. Dammed pool C. Plunge pool D. Mid-channel pool E. Run

9. A pool formed here would be a: A. Lateral scour pool B. Dammed pool C. Plunge pool D. Mid-channel pool E. Run

10. Name this mesohabitat: A. High gradient riffle B. Run C. Low gradient riffle D. Pool E. Cascade

IN-CLASS PROBLEM #3
Selecting a Reference Reach
BLM Training Course 7000-12

The Problem:

Selecting a suitable reference reach can be a challenging and thought provoking undertaking. In this exercise, we will be comparing the characteristics of five Clark Fork River test reaches with those of three possible reference reaches. Your objective is to select a reference reach for each of the five test reaches based upon the photographs and data provided. In this case, the "disturbance" was water quality related, so no water quality data are presented.

Your assignment is as follows:

1. Review the Power Point photographs of the eight reaches, noting valley, channel, and habitat characteristics.

2. Review the attached data plots which compare the test and reference reaches.

3. Develop a "decision matrix" to help you compare and contrast the reaches. An example matrix is provided below.

4. Select a reference for each of the five Clark Fork test reaches.

5. Present, discuss and defend your choices.

RATING FOR EACH CHARACTERISTIC

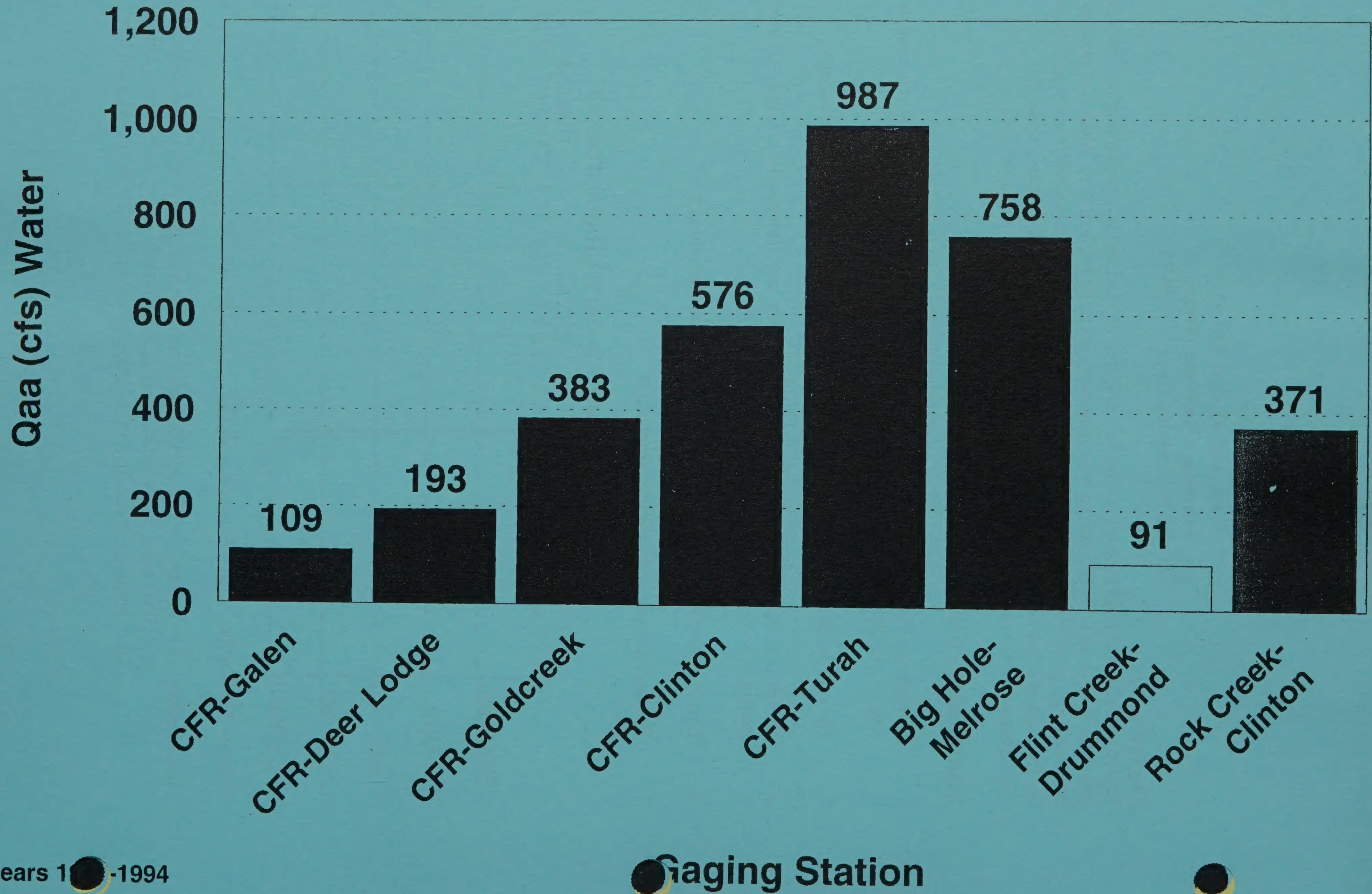
	Big Hole	Flint Ck	Rock Ck
	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12
CFR1(Galen)			
CFR2(DL)			
CFR3(GC)			
CFR4(Clint)			
CFR5(Turah)			

Ratings: 1 = Similar 2 = Somewhat similar 3 = Not similar

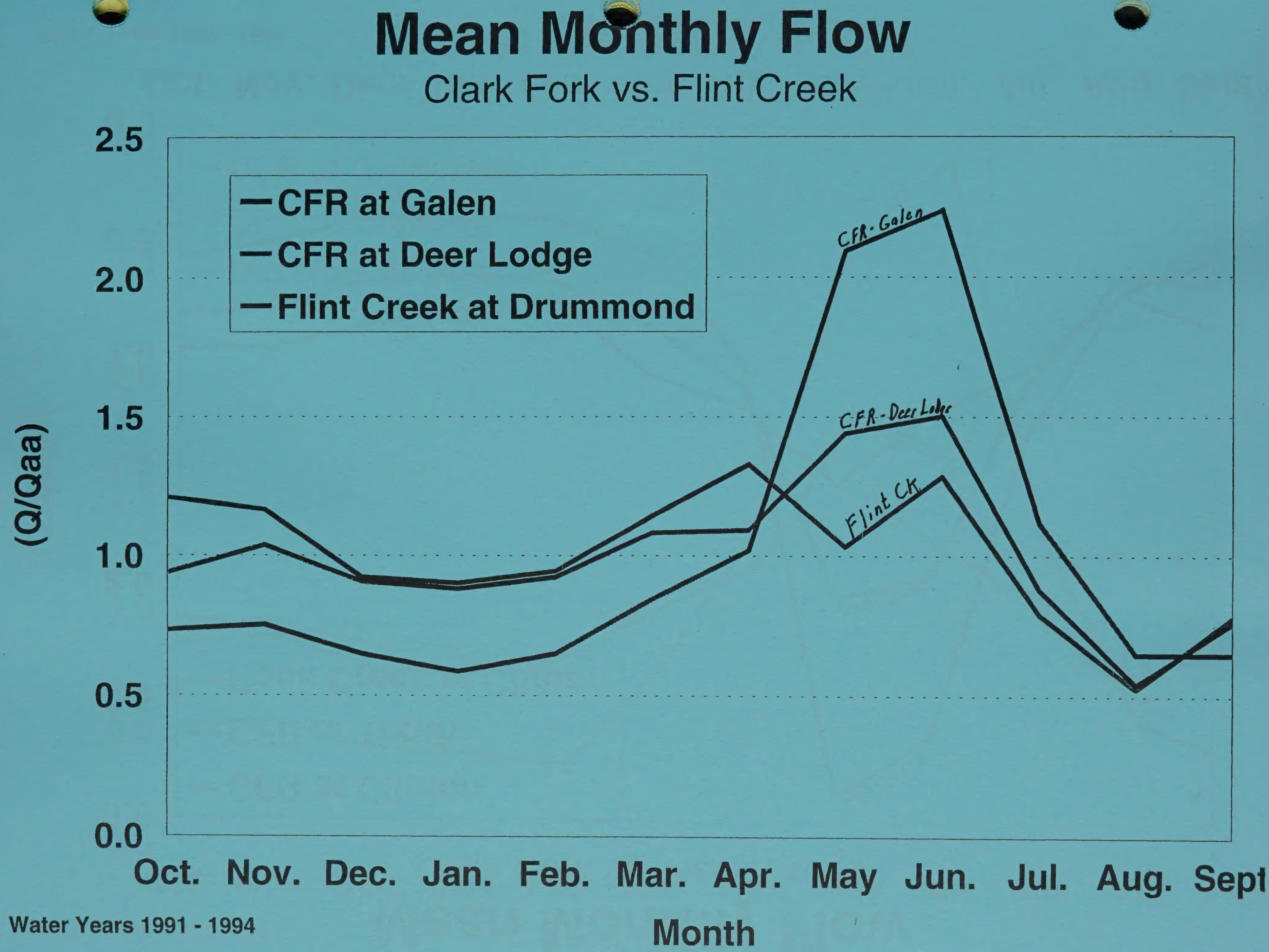
Characteristics: 1 = Valley; 2 = Channel; 3 = Habitat; 4 = Ave. Ann. Flow; 5 = Monthly Flows
6 = Basin area; 7 = Main ch. length; 8 = Channel elev.; 9 = Stream gradient;
10 = Total roads density; 11 = % altered channel; 12 = Ratio irrigated land

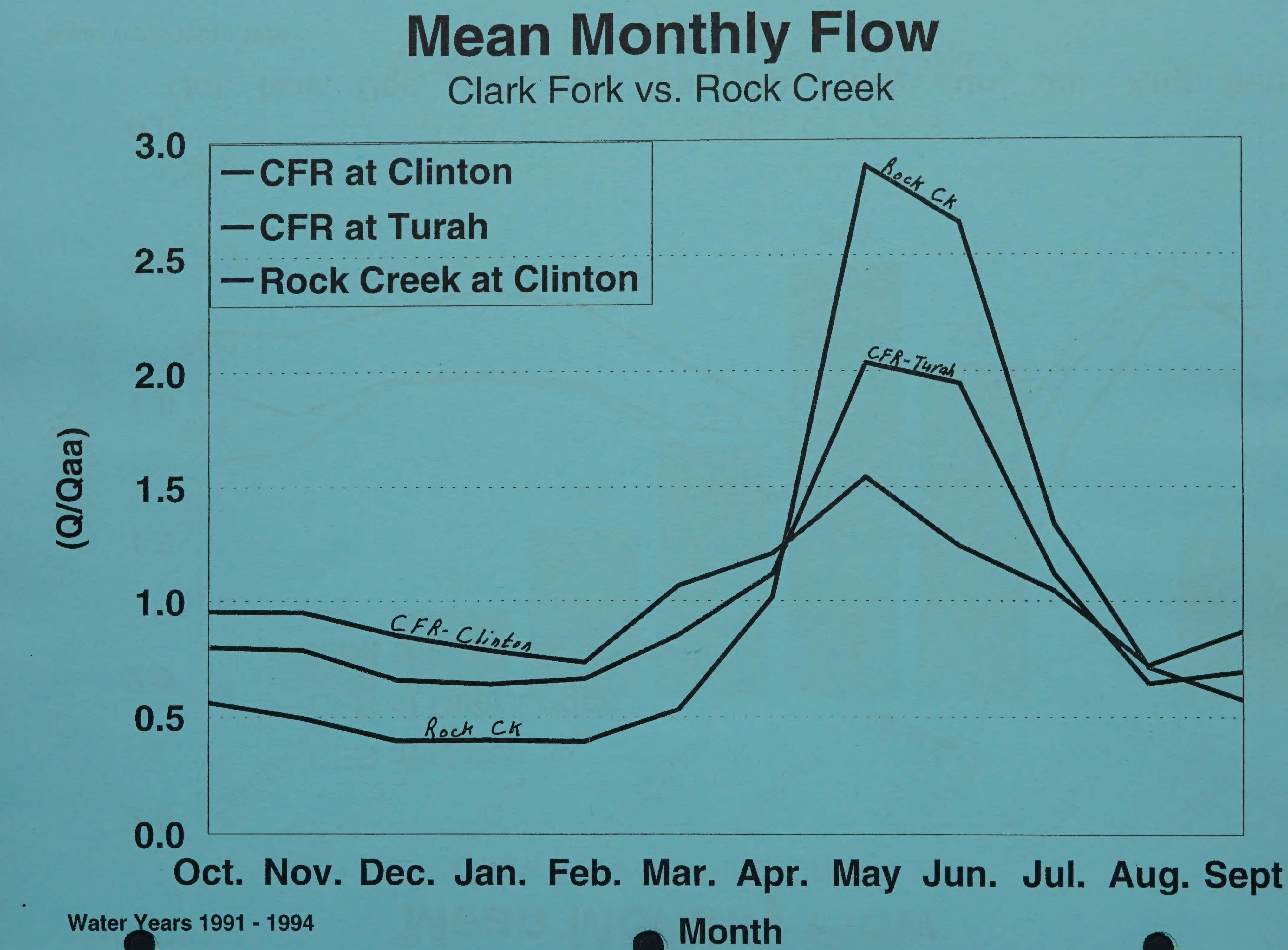
Average Annual Flow

Clark Fork vs. Control Streams



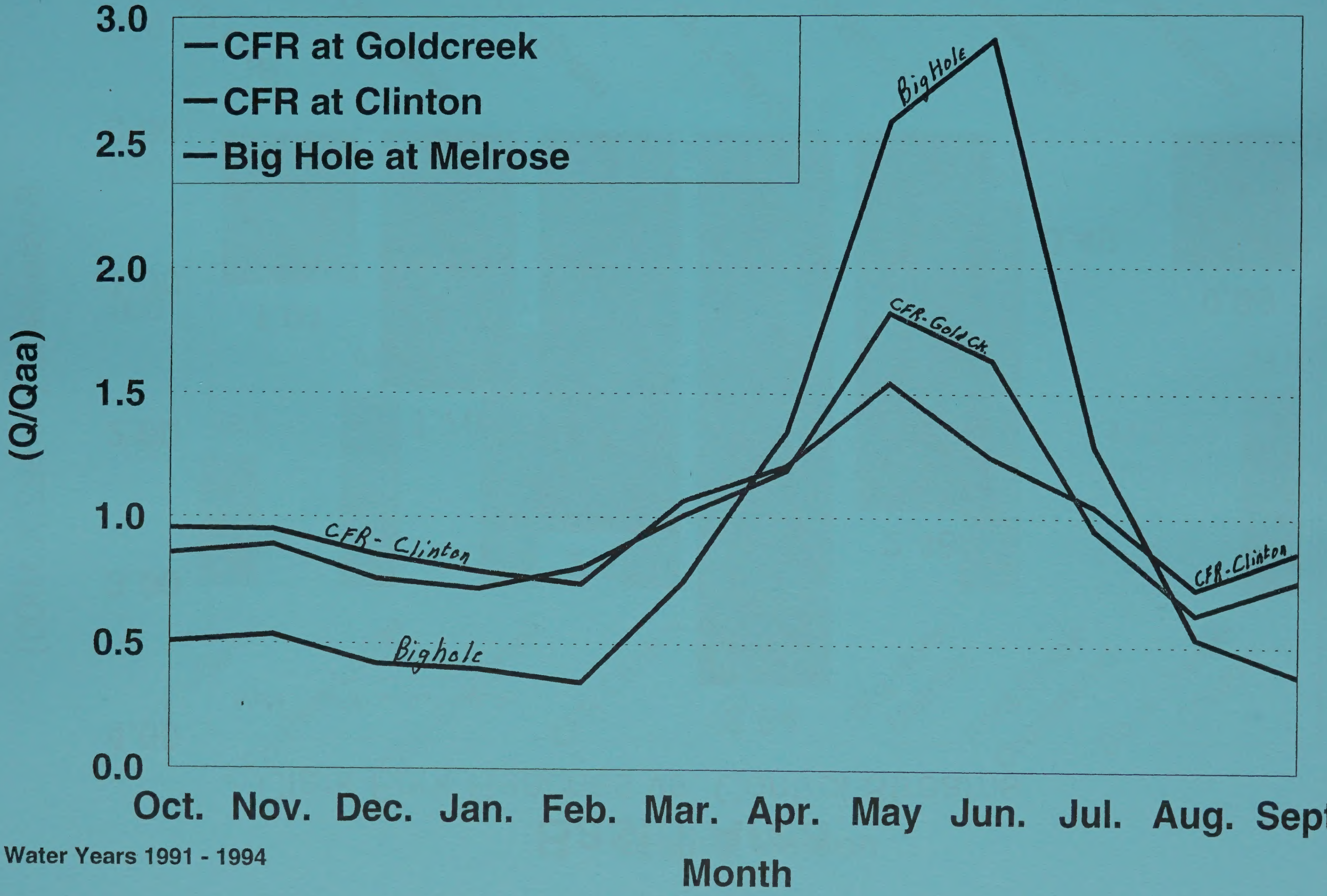
Years 1[illegible]-1994


Mean Monthly Flow
Clark Fork vs. Flint Creek
2.5
2.0
1.5
1.0
0.5
0.0
(Q/Qaa)
CFR at Galen
CFR at Deer Lodge
Flint Creek at Drummond
CFR-Galen
CFR-Deer Lodge
Flint Ck
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept
Month
Water Years 1991 - 1994

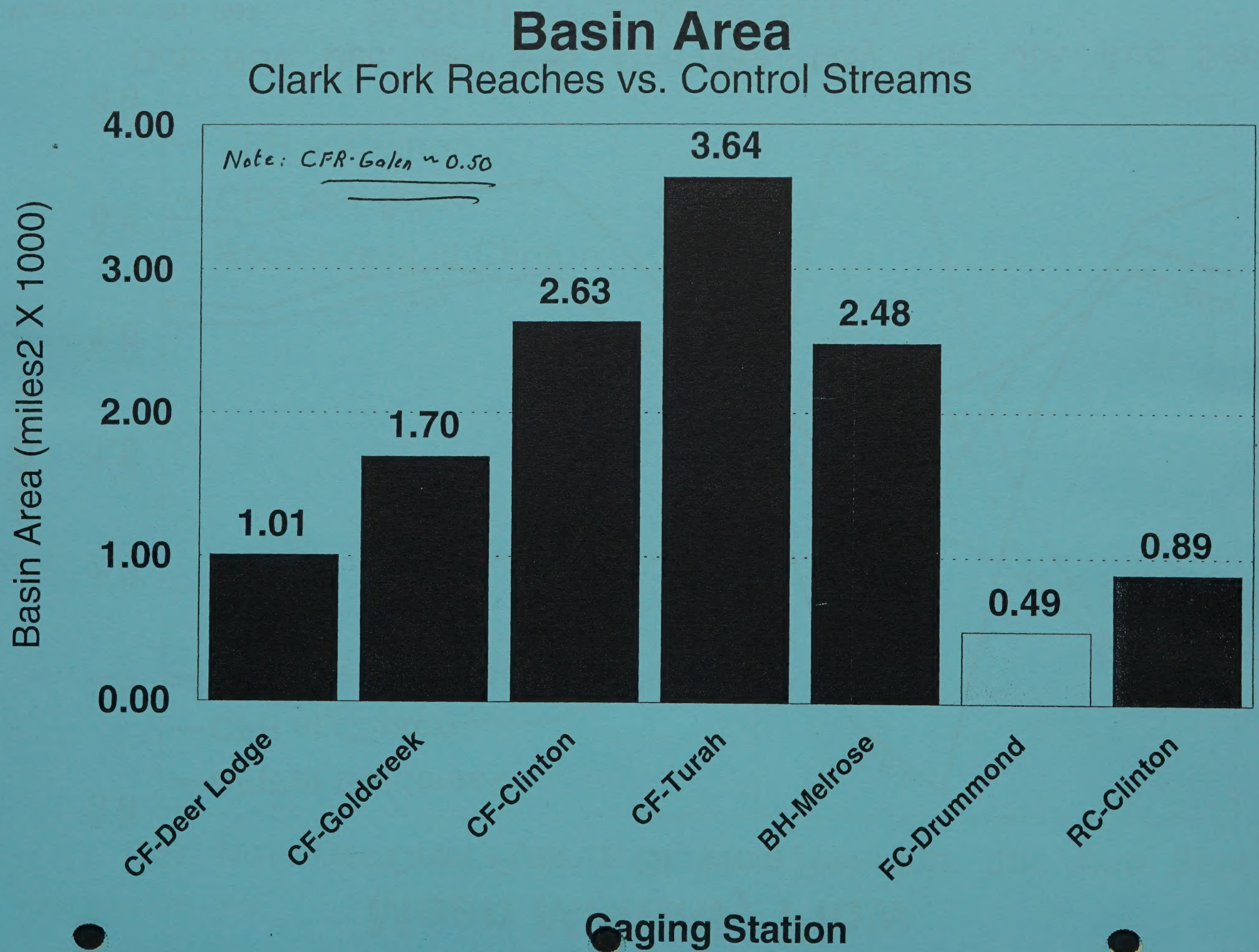

Mean Monthly Flow
Clark Fork vs. Rock Creek
3.0
2.5
2.0
1.5
1.0
0.5
0.0
(Q/Qaa)
CFR at Clinton
CFR at Turah
Rock Creek at Clinton
Rock Ck
CFR-Turah
CFR-Clinton
Rock Ck
Oct.
Nov.
Dec.
Jan.
Feb.
Mar.
Apr.
May
Jun.
Jul.
Aug.
Sept
Month
Water Years 1991 - 1994

Mean Monthly Flow

Clark Fork vs. Big Hole River



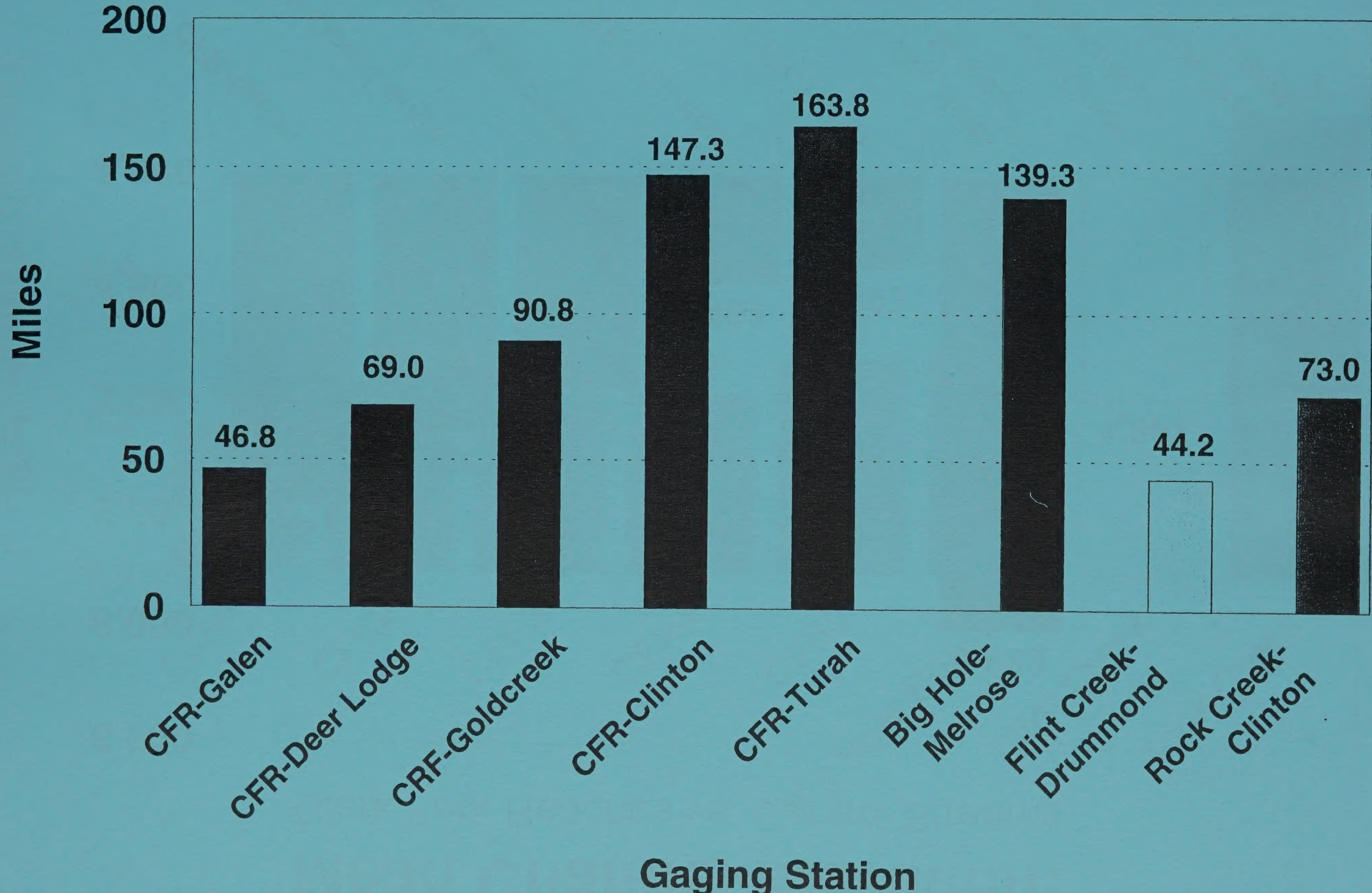
Water Years 1991 - 1994

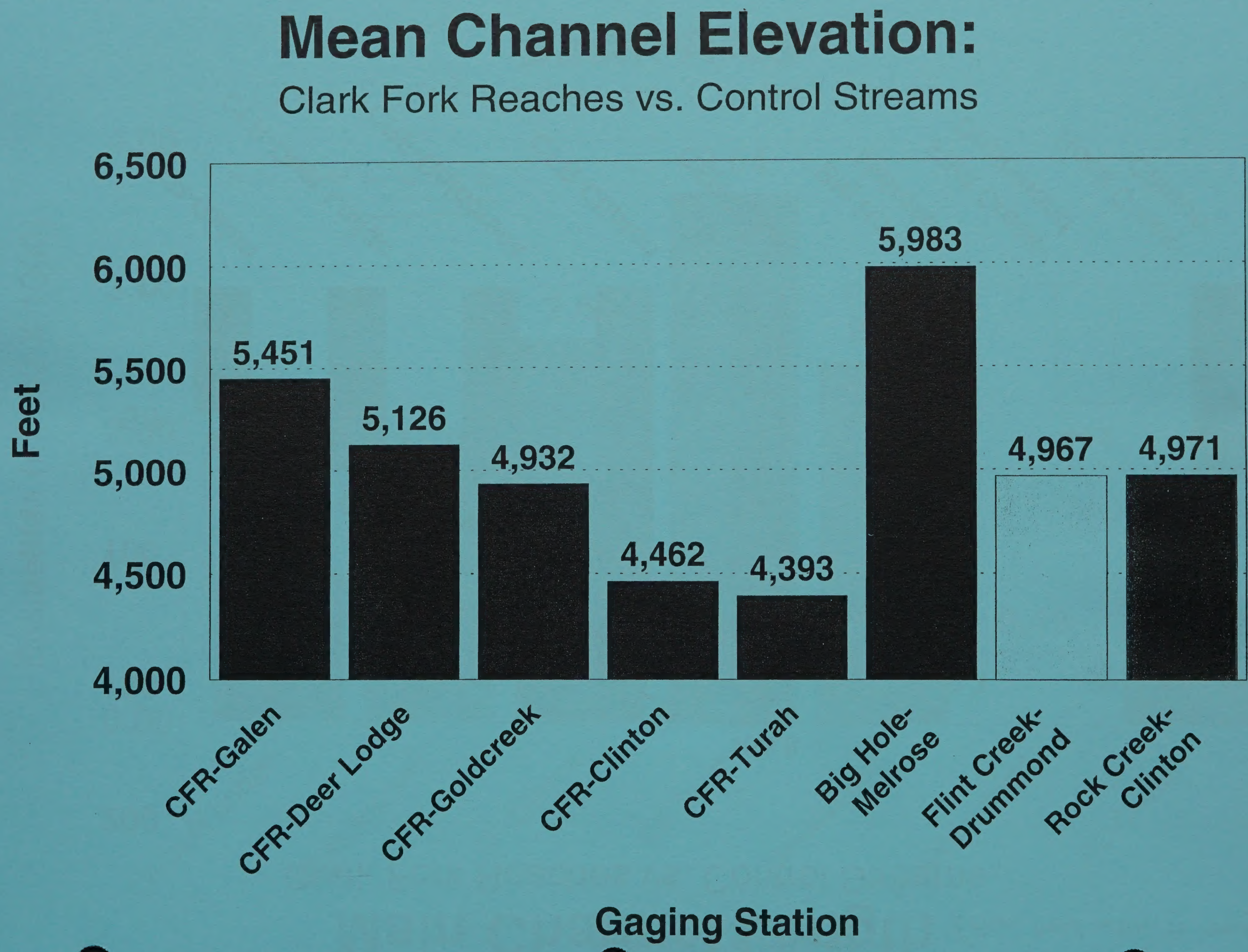


Basin Area
Clark Fork Reaches vs. Control Streams
Basin Area (miles2 X 1000)
4.00
3.00
2.00
1.00
0.00
Note: CFR-Galen ~ 0.50
1.01
1.70
2.63
3.64
2.48
0.49
0.89
CF-Deer Lodge
CF-Goldcreek
CF-Clinton
CF-Turah
BH-Melrose
FC-Drummond
RC-Clinton
Gaging Station

Main Channel Length (from head waters to reach)

Clark Fork Reaches vs. Control Streams

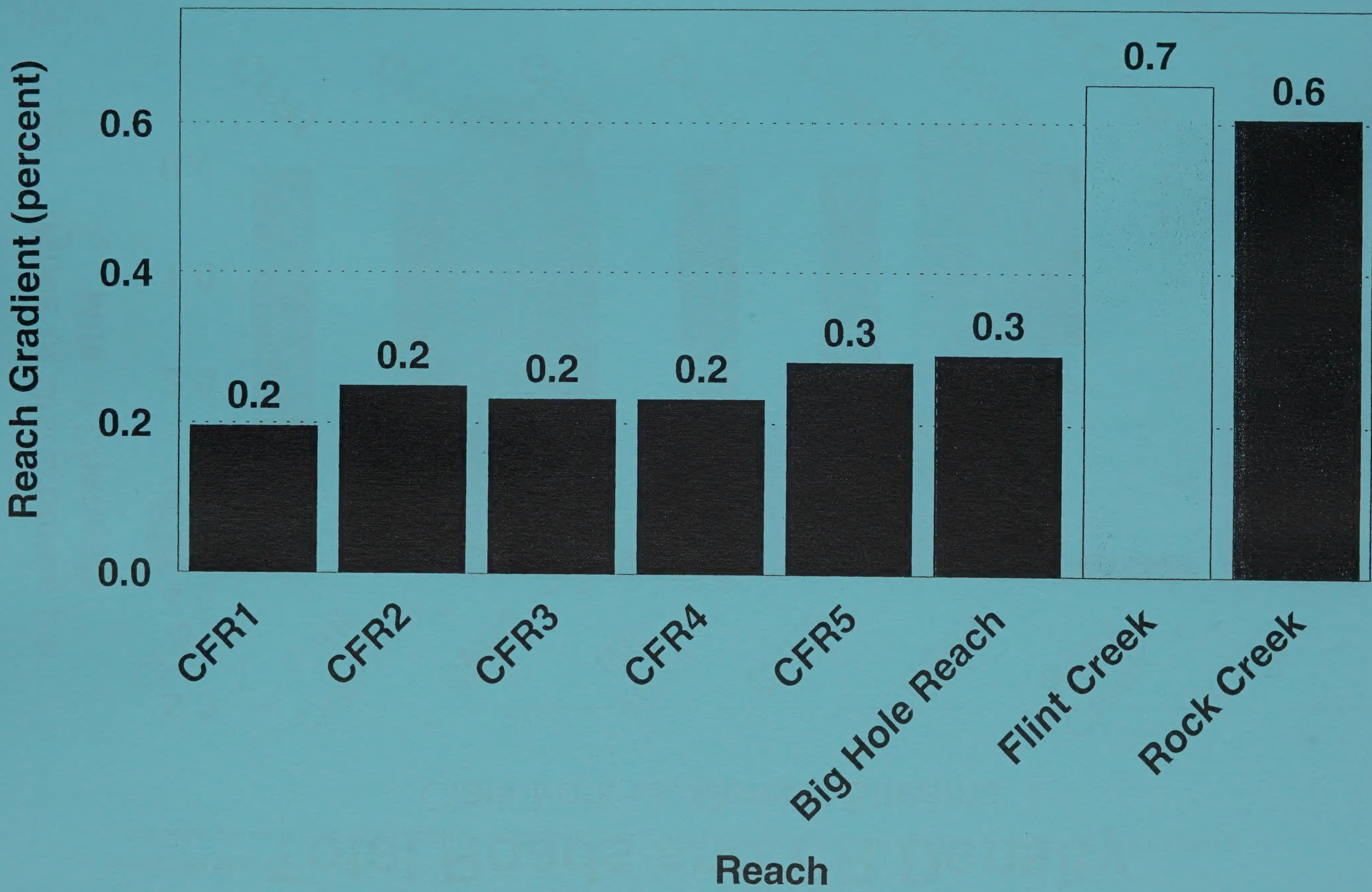


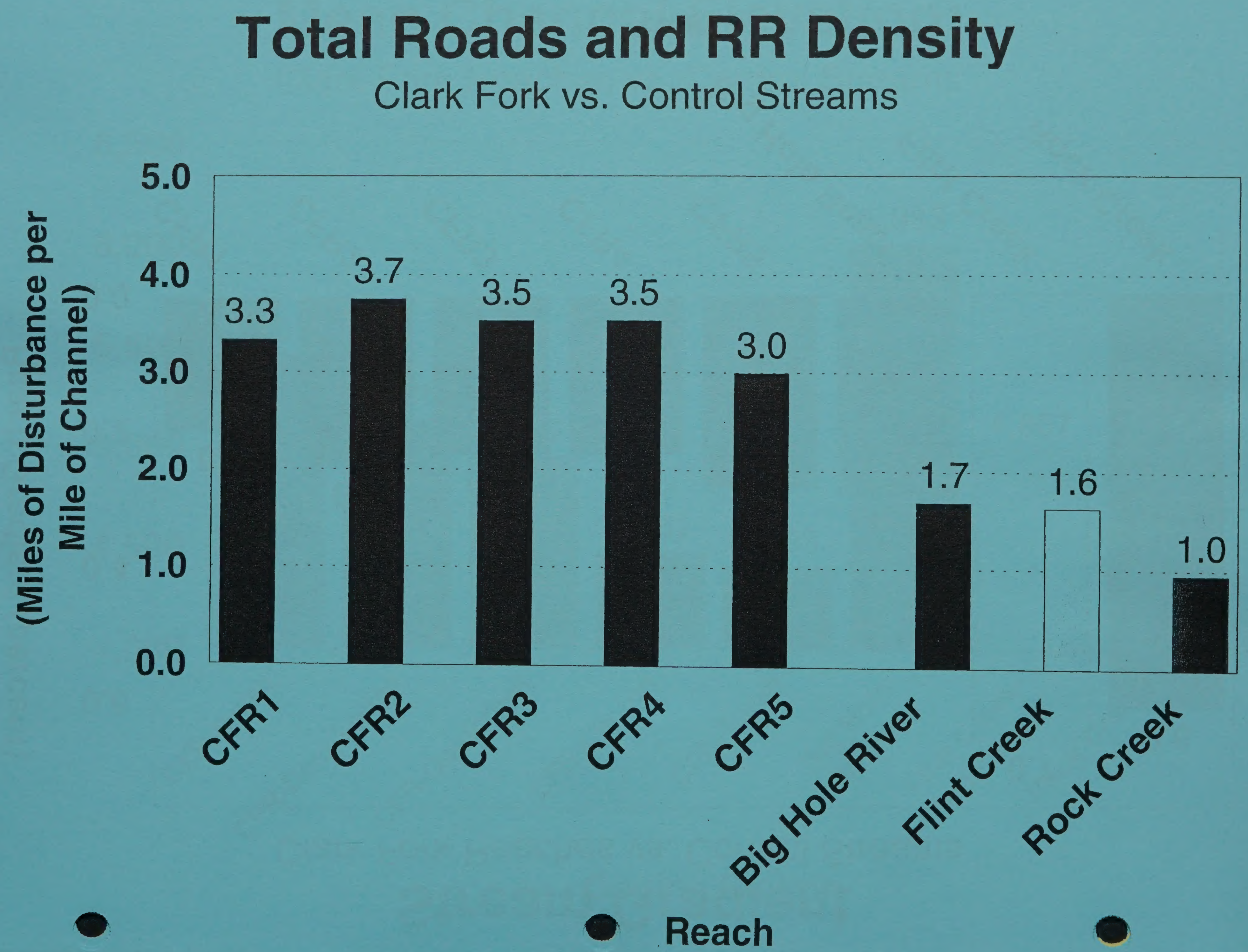


Mean Channel Elevation:
Clark Fork Reaches vs. Control Streams
6,500
6,000
5,500
5,000
4,500
4,000
Feet
5,451
5,126
4,932
4,462
4,393
5,983
4,967
4,971
CFR-Galen
CFR-Deer Lodge
CFR-Goldcreek
CFR-Clinton
CFR-Turah
Big Hole-Melrose
Flint Creek-Drummond
Rock Creek-Clinton
Gaging Station

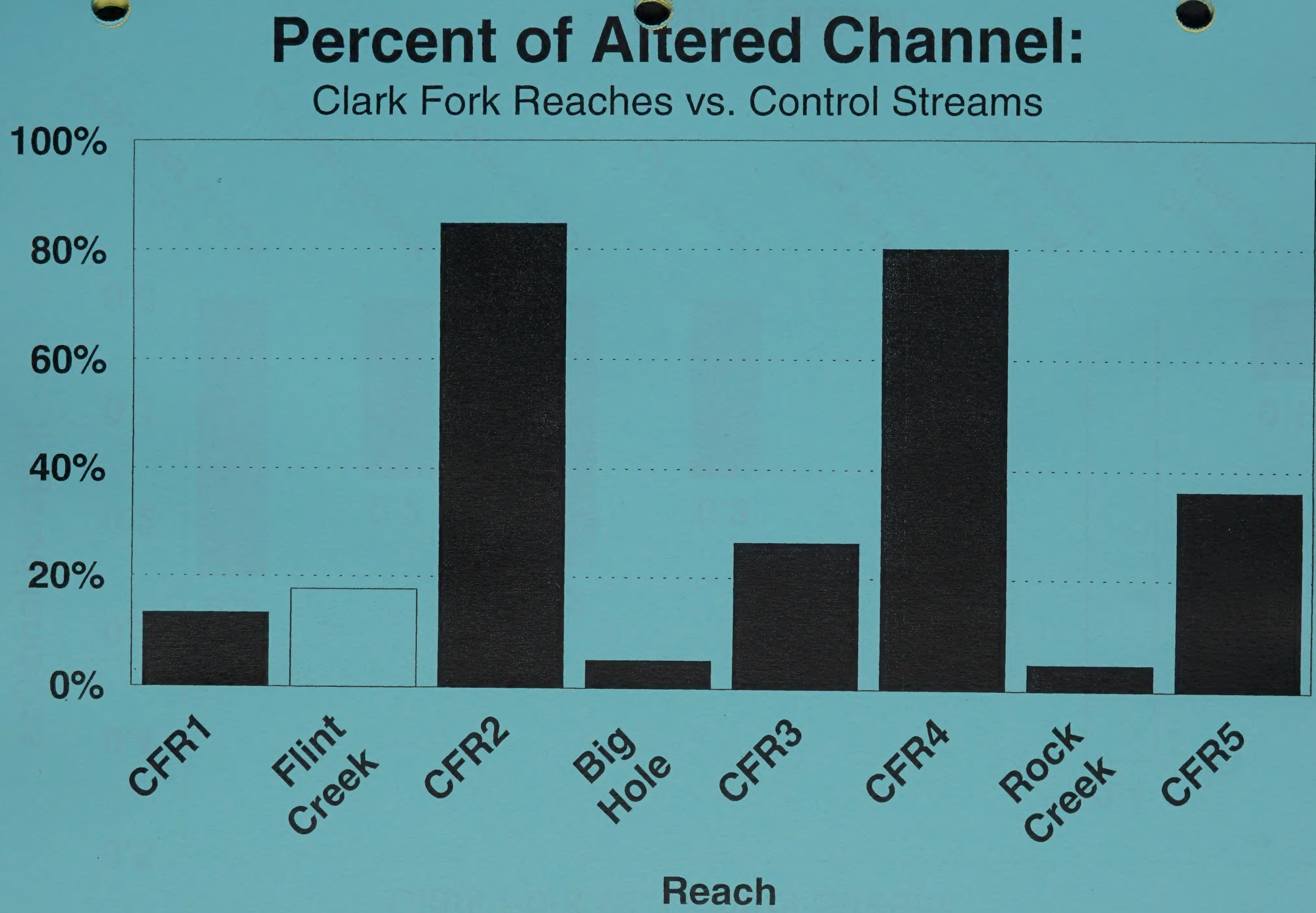
Stream Gradient

Clark Fork Reaches vs. Control Streams

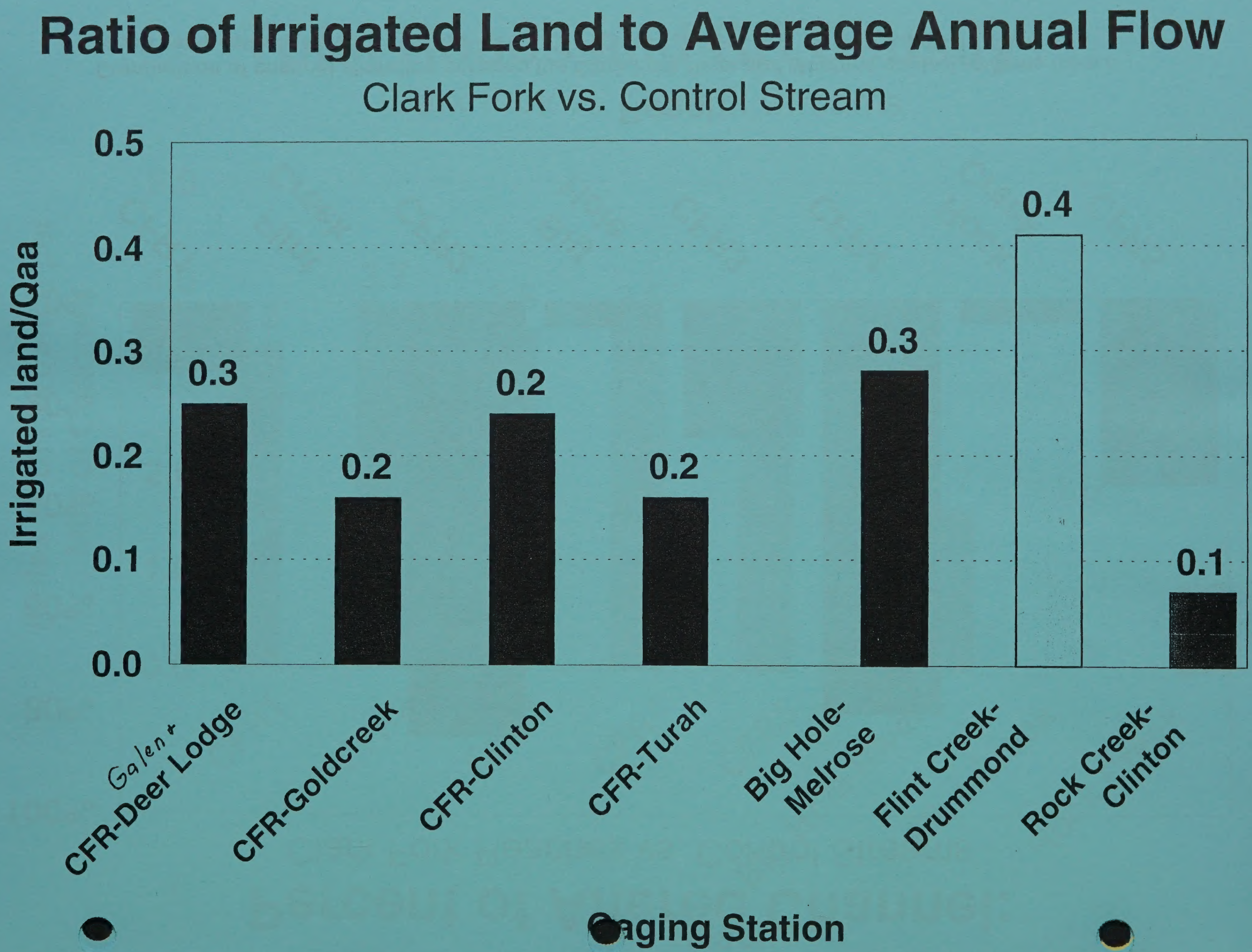




Total Roads and RR Density
Clark Fork vs. Control Streams
(Miles of Disturbance per Mile of Channel)
5.0
4.0
3.0
2.0
1.0
0.0
3.3
3.7
3.5
3.5
3.0
1.7
1.6
1.0
CFR1
CFR2
CFR3
CFR4
CFR5
Big Hole River
Flint Creek
Rock Creek
Reach



Comparison of channel alteration between the Clark Fork River and Montana control streams from a reach perspective.


Ratio of Irrigated Land to Average Annual Flow
Clark Fork vs. Control Stream
Irrigated land/Qaa
0.5
0.4
0.3
0.2
0.1
0.0
0.3
0.2
0.2
0.2
0.3
0.4
0.1
Galen+
CFR-Deer Lodge
CFR-Goldcreek
CFR-Clinton
CFR-Turah
Big Hole-Melrose
Flint Creek-Drummond
Rock Creek-Clinton
Gaging Station

IN-CLASS PROBLEM #4
Applying SSTemp for Limiting Factor Analysis
BLM Training Course No. 7000-12

The Problem:

As discussed in class, SSTemp is an easily applied model that can be used to evaluate water temperature as a potential limiting factor for a target species and to investigate the influence of possible management actions. In this exercise, you will be predicting mean daily and maximum water temperatures in the Middle Rio Grande from Albuquerque downstream 12.3 miles to Isleta based upon a given set of hydrologic and climatologic conditions. Your target species will be the Rio Grande silvery minnow.

Your assignment is as follows:

1. Working in pairs, load the SSTemp software and review the Power Point photos.

2. Input the attached data on the SSTemp program data screen.

3. Run the model to determine the predicted mean and maximum daily water temperature at Isleta on September 3.

4. Based upon the attached hypothetical water temperature suitability index plot for Rio Grande silvery minnow, how has temperature suitability changed between Albuquerque and Isleta?

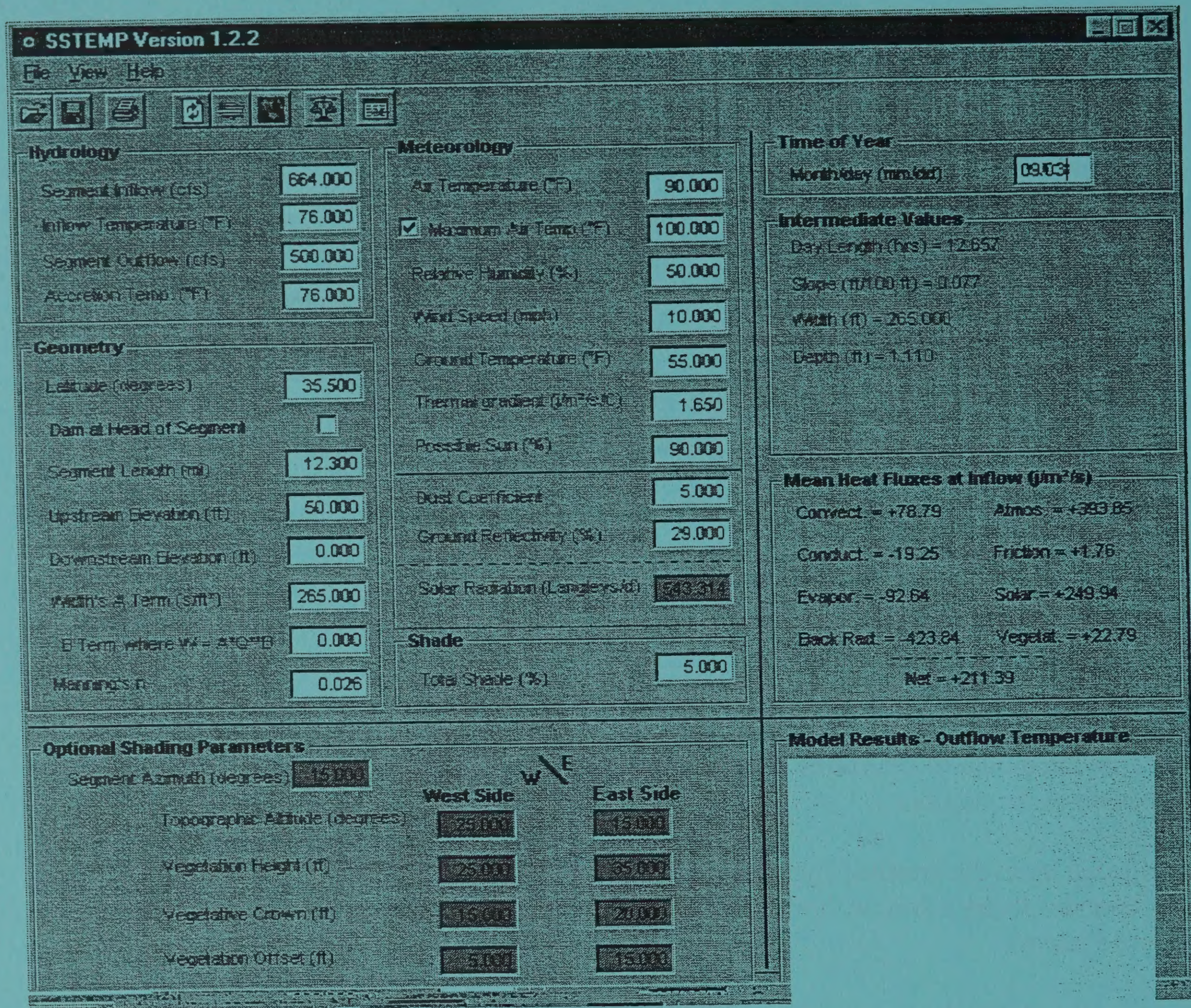
5. For the climatologic conditions on which this problem is based, do you consider water temperature to be a limiting factor for the minnow?

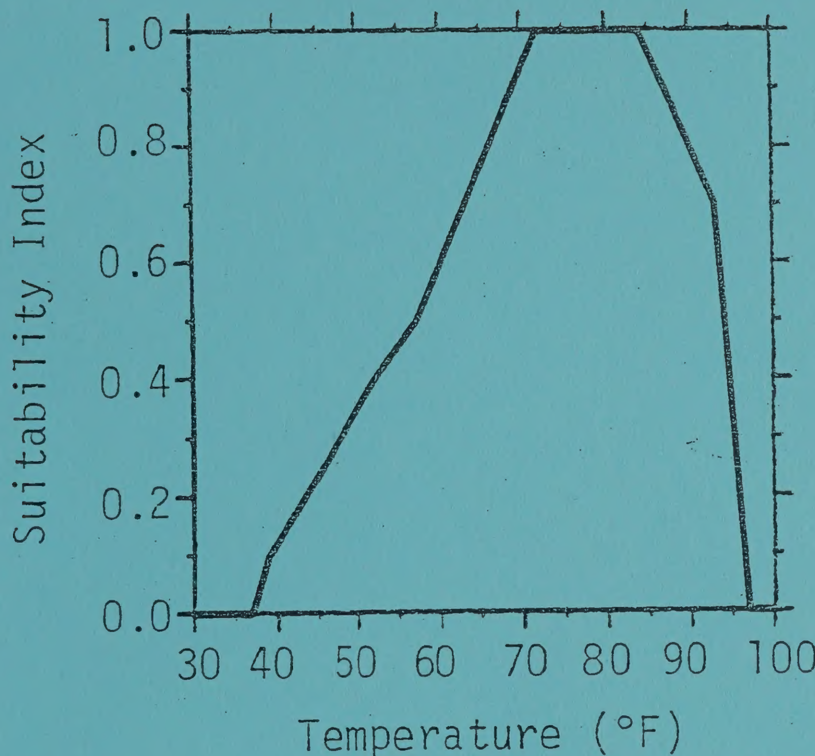
6. Total shade has been set at 5%. "Game" with this potential management variable. How are mean and maximum temperatures affected by increasing shading to 25 and 50%? How does this affect temperature suitability?

7. On the Tool Bar, go to the View Flow/Distance Matrix and inspect the various graphs. If due to drought flow were reduced 67% to 221 cfs, how is mean temperature suitability for the minnow affected?

8. If this channelized stream segment were to be re-constructed to increase meandering, thereby increasing segment length to 16.0 miles, how is mean temperature suitability for the minnow affected?

9. Discuss your results and conclusions.


SSTEMP Version 1.2.2
File View Help
Hydrology
Segment Inflow (cfs) 664.000
Inflow Temperature (°F) 76.000
Segment Outflow (cfs) 500.000
Accretion Temp. (°F) 76.000
Geometry
Latitude (degrees) 35.500
Dam at Head of Segment
Segment Length (mi) 12.300
Upstream Elevation (ft) 50.000
Downstream Elevation (ft) 0.000
Width's A Term (s/ft²) 265.000
B Term where W = A*Q**B 0.000
Manning's n 0.026
Meteorology
Air Temperature (°F) 90.000
Maximum Air Temp (°F) 100.000
Relative Humidity (%) 50.000
Wind Speed (mph) 10.000
Ground Temperature (°F) 55.000
Thermal gradient (j/m²/s/C) 1.650
Possible Sun (%) 90.000
Dust Coefficient 5.000
Ground Reflectivity (%) 29.000
Solar Radiation (Langleys/d) 543.314
Shade
Total Shade (%) 5.000
Time of Year
Month/day (mm/dd) 09/03
Intermediate Values
Day Length (hrs) = 12.657
Slope (ft/100 ft) = 0.077
Width (ft) = 265.000
Depth (ft) = 1.110
Mean Heat Fluxes at Inflow (j/m²/s)
Convect. = +78.79
Atmos. = +393.85
Conduct. = -19.25
Friction = +1.76
Evapor. = -92.64
Solar = +249.94
Back Rad. = -423.84
Vegetat. = +22.79
Net = +211.39
Optional Shading Parameters
Segment Azimuth (degrees) 15.000
W E
West Side
East Side
Topographic Altitude (degrees) 25.000 15.000
Vegetation Height (ft) 25.000 35.000
Vegetative Crown (ft) 15.000 20.000
Vegetation Offset (ft) 5.000 15.000
Model Results - Outflow Temperature


Suitability Index
1.0
0.8
0.6
0.4
0.2
0.0
30 40 50 60 70 80 90 100
Temperature (°F)

IN-CLASS PROBLEM #5
Identifying Potential Limiting Factors Using HSI Models
BLM Training Course No. 7000-12

The Problem:

The Habitat Suitability Index (HSI) models developed by the U.S. Fish and Wildlife Service are a user-friendly approach to identifying potential limiting factors for aquatic habitat restoration. In this exercise we will apply the cutthroat trout model, one of many that has been developed for terrestrial and aquatic species nationwide. Application of the model will allow us to identify for which life stage habitat quality is potentially most limiting, as well as those habitat variables most responsible for impaired habitat quality. Once these variables have been identified, concise yet quantifiable restoration objective statements can be written.

Your assignment is as follows:

1. Review the Cutthroat Trout HSI manual provided in your handouts, paying particular attention to a) Figure 1 on page 8 which illustrates the relationship between model variables, components, and HSI; b) pages 11-17 which present the suitability curves for each variable; and, c) pages 22-26 which present the component and overall HSI models.

2. Review the attached sample data sets for our reference and test stream reaches. Please be sure you understand how the suitability index (SI) values for each variable were obtained.

3. Working in pairs, calculate the component (adult, juvenile, fry, embryo, and other) and species HSI scores for the reference and test reaches using the riverine models. Calculate the species HSI using the equal component value method on page 24. **To save time, let's have half the class work with the reference data and the other half with the test data. We'll post all scores on the board.**

4. For the test reach, identify which life stage(s) is potentially most limited by habitat quality based upon the component scores. Also, for all life stages, identify which habitat variables are most limiting.

5. Prioritize the habitat variables identified in Step 4, and for the top 3 (those you feel are most limiting and which can be managed for), write concise, quantitative restoration objective statements.

6. Present, discuss, and defend your findings.

Variable		Reference Data set Data	SI	Test Data set Data	SI
Max. temperature (°C)	V_1	14	1.0	16	1.0
Max. temperature (°C)	V_2	12	1.0	17	0.4
Min. dissolved O_2 (mg/l)	V_3	9	1.0	6	0.42
Ave. depth (cm)	V_4	25	0.9	18	0.6
Ave. velocity (cm/s)	V_5	30	1.0	20	0.57
% cover	V_6	20	A 0.95 J 1.0	10	A 0.65 J 0.92
Ave. gravel size (cm)	V_7	4	1.0	2.5	1.0
Dom. substrate size (cm)	V_8	15	1.0	8	0.7
Dom. substrate class	V_9	A	1.0	B	0.6
% pools	V_{10}	55	1.0	10	0.46
% Alloch. vegetation	V_{11}	225	1.0	200	1.0
% bank vegetation	V_{12}	95	1.0	40	0.5
Max. pH	V_{13}	7.1	1.0	7.2	1.0
% Ann. base flow	V_{14}	37	0.8	25	0.5
Pool class	V_{15}	A	1.0	C	0.3
% fines (A)	V_{16}	5	1.0	20	0.5
% fines (B)	V_{16}	15	0.9	30	0.6
% shade	V_{17}	60	1.0	60	1.0

IN-CLASS PROBLEM #6
Applying IHA and RVA
BLM Training Course No. 7000-12

The Problem:

The Indicators of Hydrologic Alteration (IHA) procedure can be used to compare a river's stream flow regime before and after a water management change, thereby quantifying the magnitude and direction of change for 32 parameters considered to be of ecological significance. The Range of Variability Approach (RVA) can then be applied to establish target ranges for each of the 32 flow parameters, which if met, will help to restore a regime more similar to the pre-impact condition. The degree to which the RVA target range is not attained is considered a measure of hydrologic alteration. In this exercise, we will apply IHA and RVA to assess the degree of hydrologic alteration which has occurred as a result of the construction of Cochiti dam on the Middle Rio Grande in the early 1970's, 50 miles upstream of Albuquerque, NM. Our pre-impact period-of-record will be 1942 - 1970, while our post-impact period will be 1975 - 1999.

Your assignment is as follows:

1. Load the CD containing the program and follow the instructions on the attached page to run your analysis.

2. From the mass of results you will obtain, locate and review a) the mean monthly flow alteration plot; b) the IHA Parametric Scorecard table; and c) the IHA Parametric RVA Scorecard table.

3. Following your review of results, answer the following:
   a) Are mean monthly flows higher or lower since Cochiti dam was built?___higher___
   b) Are days of zero flow more or less common since Cochiti was built?___less___
   c) Is the date of maximum flow earlier or later in the year since Cochiti?______
   d) Which month has seen the greatest flow increase (in cfs) since Cochiti?___June___
   e) Are flows generally more or less variable since Cochiti?___same___
   f) Which Parameter Group has been most affected by Cochiti?______
   g) Which month has the widest RVA target flow range?______
   h) For which month have post-Cochiti flows best met the RVA targets?______
   i) For which month have post-Cochiti flows least met the RVA targets?______
   j) Have post-Cochiti flows best met the "minimum" or "maximum" RVA targets?______

4. Discuss the possible biological significance of these hydrologic alterations for the Rio Grande silvery minnow.

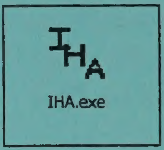
Indicators of Hydrologic Alteration
Attachment to Problem Set 6

Load CD into Drive. Double Click IHA folder
"Unzip" IHA onto your computer.

IHA Program Setup:
Double-click the "**setup**" program to load IHA program.
(It is highly recommended you put this program right in your root directory and do not use spaces or long names as the directory name; i.e. C:/IHA

Next, copy "**Batchfor.exe**" from the CD to the directory where you set up IHA. This is a patch for a bug found.

Open **IHA.**



Data file we will use is **RGAlbdis.dat** located in the IHA folder on the CD.
Copy this file to your directory (makes it easier to use). This file is already in IHA format.

From pull–down menu, run "Wizard" off the **IHA Analysis.**

Your parameters are:
Data file is : **RGAlbdis.dat**
Data file is already in IHA format (on your CD or in the folder where you loaded IHA).
We are comparing two time periods.
Pre-Impact period is **1942-1970**
Impact year was **1971**
Post-Impact Period is **1975-1999**
Run a parametric analysis

Name the files whatever you like (keeping them short) or use the default filenames.

IN-CLASS PROBLEM #7
WinXSPRO Applications for Instream Flow Analysis
BLM Training Course No. 7000-12

The Problem:

As we've discussed, WinXSPRO is a user-friendly program which allows you to model the hydraulics of single stream cross-sections over a range of flow conditions. These capabilities allow the program to be used for some instream flow applications. In this exercise, you will model a cross-section from a small cutthroat trout stream and use the output to develop instream flow recommendations.

Your assignment is as follows:

1. Load the WinXSPRO program and review.

2. Input the cross-section data provided on the attached page. These data were collected at water stage = 1.8 ft.

3. Run the program using a constant slope of 0.003 and a Manning's n of 0.04 for low stage and 0.03 for high stage. The range of water stage you should model are from 0.5 ft up to 2.4 ft.

4. Once you've obtained your model results, check your output using the following field measured flow values: 1.2 ft stage = 26 cfs; 1.7 ft stage = 70 cfs; 1.8 ft stage = 78 cfs. If your output is more than 5-10% different than these values, better double-check things.

5. Plot wetted perimeter against flow and identify the inflection point. The flow at the point of inflection is commonly recommended as a late season baseflow because it avoids the flow range having the greatest rate of habitat loss and it protects a high percentage of the available rearing (food and cover) habitat.

6. Suitable cutthroat trout spawning habitat in smaller streams has been described as having a water velocity of 1.0 to 2.0 ft/s, a water depth of at least 0.6 ft, and a gravel substrate. Assuming the substrate is gravel, inspect your hydraulic output table and identify the flow for which mean velocity and depth first meet these criteria. This flow can serve as a spawning and incubation recommendation.

7. Compare and discuss your recommendations.

Cross Section Data for Problem Set

Location (ft)	Tape Height (Ft)
0	0.3
1	0.92
2	1.5
3.5	1.54
5	1.66
6.5	1.77
8	1.83
9.5	1.88
11	1.92
12.5	2.00
14	2.03
15.5	2.05
17	2.09
18.5	2.11
20	2.13
21.5	2.24
23	2.45
24.5	2.64
26	2.72
27	1.78
27.4	0.92
28	0.3

IN-CLASS PROBLEM #8
Using RHABSIM to Evaluate Instream Flow Trade-Offs
BLM Training Course No. 7000-12

<u>The Problem:</u>

RHABSIM is a somewhat more user-friendly version of the PHABSIM (Physical Habitat Simulation) model, a key component of the IFIM (Instream Flow Incremental Method). This approach to instream flow determination is likely the most universally applied procedure of its kind and has been used world-wide to develop instream flow recommendations for a myriad of aquatic species. In this exercise, you will apply the output of the RHABSIM model to develop, justify, and defend monthly instream flow recommendations for a small stream having three species of trout. The information provided on the attached pages includes:

1) WUA plots for 3 salmonid species and life stages
2) WUA summary table by species and life stage
3) Mean monthly hydrograph plot
4) Flow duration table

Assignment: (work in pairs)

1) Develop a periodicity chart for each species. (4 charts attached)

2) Using WUA information, determine optimum flow for each month and life stage for each species.

3) Using the 4th periodicity chart, combine the optimum flows for each species. life stage, and month.

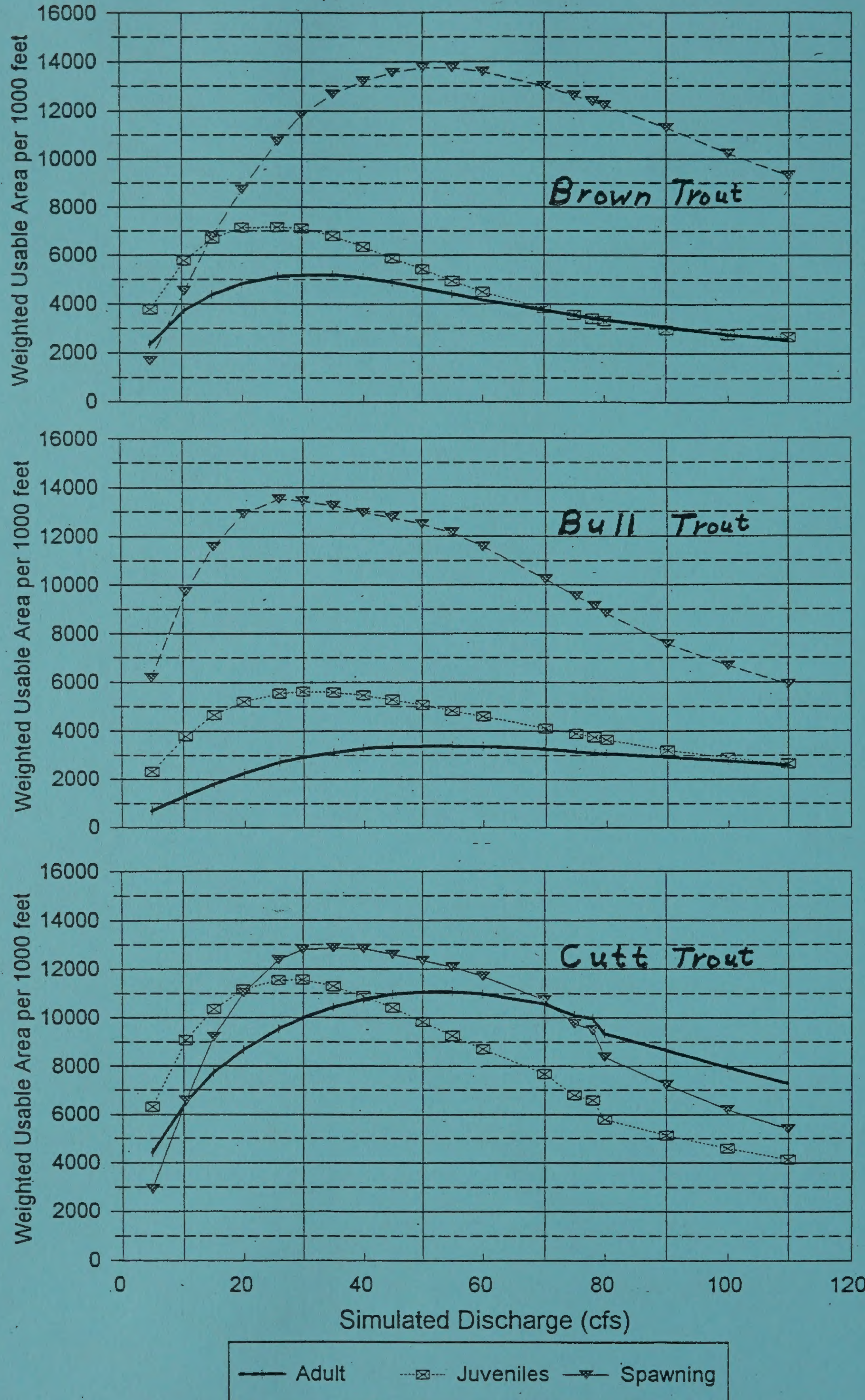
4) Evaluate instream flow trade-offs by month, keeping in mind that both bull trout and cutthroat trout are considered "sensitive" species (for the purposes of this exercise).

5) Compare monthly instream flows to historic hydrograph and flow duration values.

6) Recommend an instream flow for each month. The recommendations of all pairs will be tallied on the board at the front of the room.

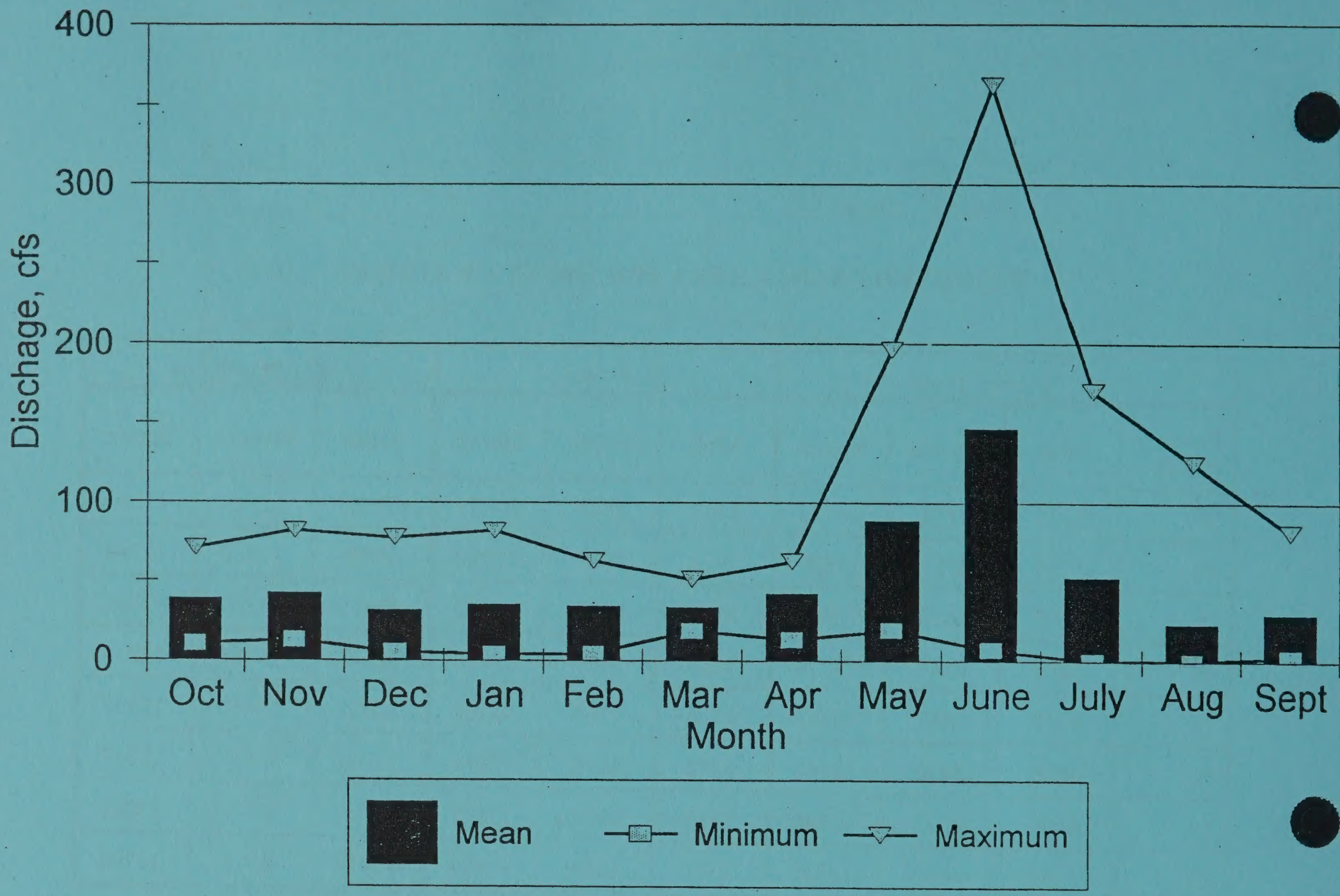
7) Compare your recommendations with the others.

8) Be prepared to discuss and defend your recommendations!


Brown Trout
Bull Trout
Cutt Trout
Weighted Usable Area per 1000 feet
Simulated Discharge (cfs)
Adult
Juveniles
Spawning

WEIGHTED USABLE AREA PER 1000 FT OF STREAM

	Brown Trout			Bull Trout			Cutt Trout		
Flow (CFS)	Adult	Juvenile	Spawn	Adult	Juvenile	Spawn	Adult	Juvenile	Spawn
26	5115	7178	10742	2703	5549	14033	9528	11549	12364
30	5186	7121	11829	2914	5623	13990	9988	11552	12794
35	5197	6816	12667	3117	5605	13779	10432	11287	12864
40	5080	6347	13214	3268	5463	13462	10746	10888	12836
45	4889	5887	13575	3356	5294	13208	10951	10417	12597
50	4638	5420	13762	3372	5078	12889	11060	9841	12337
55	4400	4937	13749	3375	4839	12507	11062	9271	12081
60	4166	4492	13592	3358	4594	11899	10974	8719	11709



% Time Flow Equaled or Exceeded				
Flow (cfs)	Oct-Dec	Jan-March	April-June	July-Sept
20	76	79	89	43
30	63	55	78	33
40	46	42	70	29
50	33	25	60	26
60	25	12	51	23

PERIODICITY CHART

Species: Cutthroat Trout — System: Southwest River

Microhabitat Usage	J	F	M	A	M	J	J	A	S	O	N	D
Adults												
Summer resting												
Winter Resting												
Spawning												
Incubation												
Fry/Larvae												
Juvenile												
Feeding												
Aquatic source												
Adult												
Juvenile												
Fry												
Terrestrial source												
Adult												
Juvenile												
Fry												

PERIODICITY CHART

Species: Trout

System: Southwest River

Microhabitat Usage	J	F	M	A	M	J	J	A	S	O	N	D
Adults												
Summer resting												
Winter Resting												
Spawning												
Incubation												
Fry/Larvae												
Juvenile												
Feeding												
Aquatic source												
Adult												
Juvenile												
Fry												
Terrestrial source												
Adult												
Juvenile												
Fry												

(MONTH heading spans the J–D columns.)

PERIODICITY CHART

Species: Trout System: Southwest River

Microhabitat	MONTH											
Usage	J	F	M	A	M	J	J	A	S	O	N	D
Adults												
Summer resting												
Winter Resting												
Spawning												
Incubation												
Fry/Larvae												
Juvenile												
Feeding												
Aquatic source												
Adult												
Juvenile												
Fry												
Terrestrial source												
Adult												
Juvenile												
Fry												

PERIODICITY CHART

Species: Trout

System: Southwest River

Microhabitat Usage	J	F	M	A	M	J	J	A	S	O	N	D
Adults												
Summer resting												
Winter Resting												
Spawning												
Incubation												
Fry/Larvae												
Juvenile												
Feeding												
Aquatic source												
Adult												
Juvenile												
Fry												
Terrestrial source												
Adult												
Juvenile												
Fry												

$HL = (\tan \theta L) XL - [G(XL)^2 / 2 (VF \cos \theta L)^2]$

IN-CLASS PROBLEM #9
Barrier Analysis for Cutthroat Trout
BLM Training Course No. 7000-12

$\tan A = a/b$
$\cos A = b/c$

The Problem:

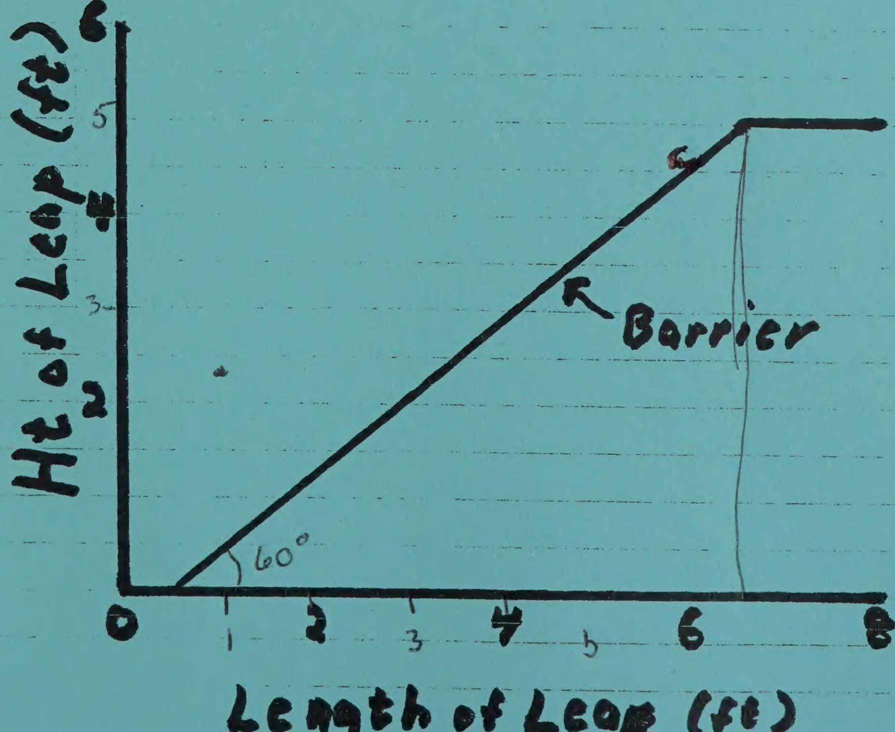
Are cutthroat trout able to pass the barrier presented on the plot below during their spring spawning migration? Assuming a burst speed of 13.0 ft/s and a leap angle of 60 degrees, analyze the barrier to determine if fish can pass using the leaping equation presented in lecture.

Plot the leaping curve on the barrier plot.

If the fish cannot pass, how would you physically modify the barrier, a boulder/cobble waterfall, to assure passage?

If you wanted only the hardiest fish to pass and spawn, how would you modify your restoration plan?

VFB: 13fps



XL	HL

a

$HL = (5/6)\,6 - [32.2\ ft/sec^2 (6)^2 / 2 (13.0\ ft/s (6/$

IN-CLASS PROBLEM #10
Douglas Creek Culvert Analysis & Design
BLM Training Course 7000-12

The Problem:

Engineers are planning to install a new culvert under the Douglas Creek road. The present design calls for a 154 ft steel pipe arch (12'10" x 8"4") on a 0.8% grade. Hydrologic studies indicate the culvert will carry flows ranging from 1.6 to 200 cfs during the spring runoff season, the same time during which cutthroat trout will be moving upstream to spawn.

Using the FishXing software, analyze the design the engineers are planning to use to determine if cutthroats will be able to successfully pass upstream through the culvert on their spawning run. Assume no inlet or outlet problems exist and a constant tailwater condition with 101.5 ft as the pool surface elevation and 99.0 ft as the outlet pool bottom elevation. Use the User selected swim speeds, with a prolonged speed of 4.0 ft/s for 30 minutes and a burst speed of 13.0 ft/s for 15 seconds.

If the fish cannot successfully pass through the culvert, use FishXing to re-design the culvert so that design flows can still be carried and the cutthroats can pass. The length of the culvert must remain at 154 ft.

Compare and discuss your results with the class.

IN-CLASS PROBLEM #11
Determining Design Flow
BLM Training Course 7000-12

Background:
The flood flow having a 2 year recurrence interval (Q_{F2}) is often assumed to approximate the bankfull discharge, a level commonly used as the high design flow estimate for stream restoration projects. Unfortunately, long-term U.S.G.S. gage records seldom exist for stream reaches where restoration efforts are planned. As a result, hydrologists have developed easily applied methods for estimating the needed design flows based upon either watershed or channel characteristics. This exercise will give you experience in applying these estimation techniques and comparing the results to flood frequency analysis of 25 years of gage records.

The Problem:
Flood frequency analysis of the 25 year period-of-record at USGS gage #06274500, Greybull River near Pitchfork, WY yields the following results:

Annual Exceedance Probability	Streamflow (cfs)	
0.99	720	
0.95	952	
0.90	1116	
0.80	1367	
0.50	2081	= QF2 = 50% probability
0.20	3305	
0.10	4283	
0.04	5724	

Based upon this analysis, what is the Q_{F2} ? 2081

Based upon Lowham's (1988) watershed characteristics model for Wyoming mountain streams, $Q_{F2} = 0.012A^{0.88}(ELEV/1000)^{3.25}$, where A is watershed area (260 sq miles) and ELEV is mean basin elevation (9000 ft), what is the estimated Q_{F2} ? 2021

Based upon Lowham's (1988) channel characteristics model for Wyoming mountain streams, $Q_{F2} = 1.94W^{1.58}$, where W is active channel width (95 ft) measured just downstream from a meander, what is the estimated Q_{F2} ? 2586

Compare your two estimates to the value based upon the gage record.

Which estimate is furthest from the gaged value? Why might this be? channel characteristics because it's based on channel width which varies greatly.

IN-CLASS PROBLEM #12
Boulder Stability
BLM Training Course 7000-12

The Problem:

You are designing a boulder placement as part of a structural habitat management program for a mountain stream. At your high design flow, water depth will be 3.0 ft at your anticipated boulder site. Channel slope is 4.0%, or 0.04. You prefer to use 2.0 ft diameter boulders since they are available close to the site.

Using the Shield's relation, Lane's relation, and the Highway Research Board relationship, as presented in the Power Point presentation, evaluate the stability of a 2.0 ft diameter boulder at your high design flow. Assume R = D; specific weight of water = 62.4lbs/ft³; specific weight of the boulder = 165lbs/ft³; and k = 0.03. water depth = 3

Shear stress acting on channel boundary = 7.49. T_o =

Critical shear using Shield's relation = 6.15. Will boulder move? ~~no~~ yes 7.5 > 6.15

Critical shear using Lane's relation = 9,997. Will boulder move? ~~yes~~ no 7.5 < 10

Critical shear using HRB relation = 8. Will boulder move? ~~yes~~ no 7.5 < 8

If results are mixed, what should you do? Note that 2 of the equations are on the boundary

- What is the consequence if the rocks move? maybe its okay
- Talk to hydraulics engineer
- Put 2' boulders in the stream to test
- Run a dimensionless calculation (per J. Fogg) & the Shield's relation may change.
- Common sense tells us to go to the location & see which size boulders are being maintained in the stream now.

IN-CLASS PROBLEM #13
Applying Stream Reach Inventory & Channel Stability Evaluation
Santa Fe River below Santa Fe, NM
BLM Training Course 7000-12

The Problem:

1. Review the Power Point photographs of the Santa Fe River.

2. Using the attached field form and the manual (handout), rate the 15 parameters.

3. Tally score and determine condition class.

4. Discuss applicability of SRI/CSE to the streams you work on. Is it a usable tool? How might you alter the parameters to better meet your needs?

Should rank within this range
100 - 120

R-1 STREAM REACH INVENTORY and CHANNEL STABILITY EVALUATION

REACH LOCATION: Survey Date______ Time______ Obs.______

Forest______ Rgr. Dist.______

P.W.I.

Stream______ W/S No. __-__-__-__-__-__-__-__

Reach Description &

Other Identification______

INVENTORY DATA: (observed or measured on this date) Side 2

Stream Width____ft.X Ave.Depth____ft.X Ave.Velocity____f/s=____Flow cfs

Reach Gradient____%, Stream Order____, Turbidity Level ______, Stream Stage______, Sinuosity Ratio ______,

Temperature °F or °C of: Air____ Water____, Others______

Key #		Stability Indicators by Classes (Fair and Poor on reverse side) EXCELLENT		GOOD	
1	Upper Banks	Bank slope gradient <30%.	(2)	Bank slope gradient 30-40%.	(4)
2	Upper Banks	No evidence of past or any potential for future mass wasting into channel.	(3)	Infrequent and/or very small. Mostly healed over. Low future potential.	(6)
3	Upper Banks	Essentially absent from immediate channel area.	(2)	Present but mostly small twigs and limbs.	(4)
4	Upper Banks	90%+ plant density. Vigor and variety suggests a deep, dense, soil binding, root mass.	(3)	70-90% density. Fewer plant species or lower vigor suggests a less dense or deep root mass.	(6)
5	Lower Banks	Ample for present plus some increases. Peak flows contained. W/D ratio <7.	(1)	Adequate. Overbank flows rare. Width to Depth (W/D) ratio 8 to 15.	(2)
6	Lower Banks	65%+ with large, angular boulders 12"+ numerous.	(2)	40 to 65%, mostly small boulders to cobbles 6-12".	(4)
7	Lower Banks	Rocks and old logs firmly embedded. Flow pattern without cutting or deposition. Pools and riffles stable.	(2)	Some present, causing erosive cross currents and minor pool filling. Obstructions and deflectors newer and less firm.	(4)
8	Lower Banks	Little or none evident. Infrequent raw banks less than 6" high generally.	(4)	Some, intermittently at outcurves and constrictions. Raw banks may be up to 12".	(8)
9	Lower Banks	Little or no enlargement of channel or point bars.	(4)	Some new increase in bar formation, mostly from coarse gravels.	(8)
10	Bottom	Sharp edges and corners, plane surfaces roughened.	(1)	Rounded corners and edges, surfaces smooth and flat.	(2)
11	Bottom	Surfaces dull, darkened, or stained. Gen. not "bright".	(1)	Mostly dull, but may have up to 35% bright surfaces.	(2)
12	Bottom	Assorted sizes tightly packed and/or overlapping.	(2)	Moderately packed with some overlapping.	(4)
13	Bottom	No change in sizes evident. Stable materials 80-100%.	(4)	Distribution shift slight. Stable materials 50-80%.	(8)
14	Bottom	Less than 5% of the bottom affected by scouring and deposition.	(6)	5-30% affected. Scour at constrictions and where grades steepen. Some deposition in pools.	(12)
15	Bottom	Abundant. Growth largely moss-like, dark green, perennial. In swift water too.	(1)	Common. Algal forms in low velocity & pool areas. Moss here too and swifter waters.	(2)
		EXCELLENT COLUMN TOTAL →		GOOD COLUMN TOTAL →	

Add values in each column and record in spaces below. Add column scores.

E.___+ G.___+ F.___+ P.___ = ______ Total Reach Score.

Adjective ratings: <38=Excellent, 39-76=Good, 77-114=Fair, 115+=Poor*

*(Scores above may be locally adjusted by Forest Hydrologist)

R1-Form 2500-5A Rev.1-75 Side 1.

Key #	Stability Indicators by Classes FAIR		POOR	
1	Bank slope gradient 40-60%.	(6)	Bank slope gradient 60%+.	(8)
2	Moderate frequency & size, with some raw spots eroded by water during high flows.	(9)	Frequent or large, causing sediment nearly yearlong OR imminent danger of same.	(12)
3	Present, volume and size are both increasing.	(6)	Moderate to heavy amounts, predominantly larger sizes.	(8)
4	50-70% density. Lower vigor and still fewer species form a somewhat shallow and discontinuous root mass.	(9)	<50% density plus fewer species & less vigor indicate poor, discontinuous, and shallow root mass.	(12)
5	Barely contains present peaks. Occassional overbank floods. W/D ratio 15 to 25.	(3)	Inadequate. Overbank flows common. W/D ratio > 25.	(4)
6	20 to 40%, with most in the 3-6" diameter class.	(6)	< 20% rock fragments of gravel sizes, 1-3" or less.	(8)
7	Moderately frequent, moderately unstable obstructions & deflectors move with high water causing bank cutting and filling of pools.	(6)	Frequent obstructions and deflectors cause bank erosion yearlong. Sediment traps full, channel migration occurring.	(8)
8	Significant. Cuts 12"-24" high. Root mat overhangs and sloughing evident.	(12)	Almost continuous cuts, some over 24" high. Failure of overhangs frequent.	(16)
9	Moderate deposition of new gravel & coarse sand on old and some new bars.	(12)	Extensive deposits of predominantly fine particles. Accelerated bar development.	(16)
10	Corners & edges well rounded in two dimensions.	(3)	Well rounded in all dimensions, surfaces smooth.	(4)
11	Mixture, 50-50% dull and bright, ± 15% ie. 35-65%.	(3)	Predominantely bright, 65%+, exposed or scoured surfaces.	(4)
12	Mostly a loose assortment with no apparent overlap.	(6)	No packing evident. Loose assortment, easily moved.	(8)
13	Moderate change in sizes. Stable materials 20-50%.	(12)	Marked distribution change. Stable materials 0-20%.	(16)
14	30-50% affected. Deposits & scour at obstructions, constrictions, and bends. Some filling of pools.	(18)	More than 50% of the bottom in a state of flux or change nearly yearlong.	(24)
15	Present but spotty, mostly in backwater areas. Seasonal blooms make rocks slick.	(3)	Perennial types scarce or absent. Yellow-green, short term bloom may be present.	(4)
	FAIR COLUMN TOTAL →		POOR COLUMN TOTAL →	

Size Composition of Bottom Materials (Total to 100%)

1. Exposed bedrock..........____%	5. Small rubble, 3"-6".....____%
2. Large boulders, 3'+ Dia....____%	6. Coarse gravel, 1"-3".....____%
3. Small boulders, 1-3'.......____%	7. Fine gravel, 0.1-1".....____%
4. Large rubble, 6"-12".......____%	8. Sand, silt, clay, muck..____%

IN-CLASS PROBLEM #14
Evaluating Log Overpour Hydraulics
BLM Training Course 7000-12

The Problem:

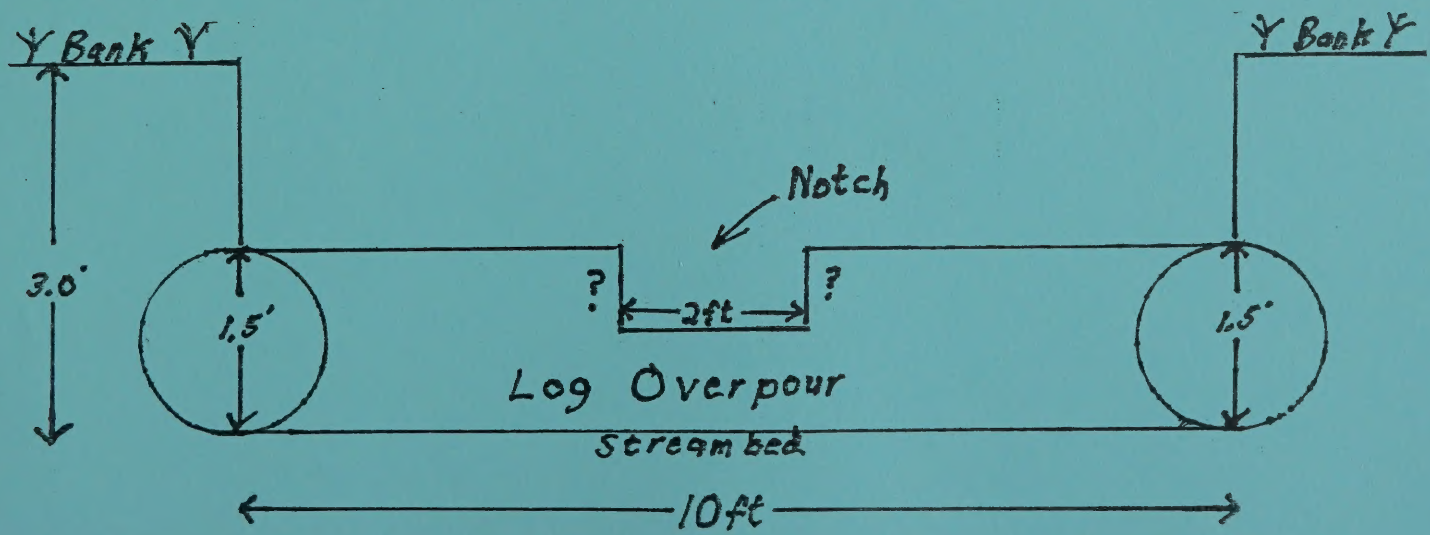
A low flow notch is often cut into a log overpour structure to concentrate the low flow into the downstream plunge pool and to keep the entire log continually wetted to prevent rot. You are designing a log overpour for a small stream that is 10 ft wide and has a bankfull depth of 3.0 ft. Your design low flow is 2.0 cfs and design high flow is 50 cfs. The elevation of the top of your log overpour (excluding the low flow notch) will be 1.5 ft above the streambed. See the diagram below.

Using the weir flow equation, solve the following:

$Q = cLH^{3/2}$, where
- Q = flow (cfs)
- c = 2.5, a head loss coefficient for log weirs
- L = weir length (ft)
- H = depth, or head, over the weir (ft)

1) If the desired width of your low flow notch is 2.0 ft, how deep should the notch be to just pass your design low flow?

2) Taking into consideration the depth of the low flow notch determined in Question 1, will your high design flow of 50 cfs be able to pass the log overpour structure without spilling over the top of the stream banks?



IN-CLASS PROBLEM #15
Using WinXSPRO to Evaluate Restoration Options
BLM Training Course No. 7000-12

The Problem:

WinXSPRO is a user-friendly computer program that can be applied to the solution of many aquatic habitat restoration questions. Based upon data from a single cross-section, both hydraulic and sediment transport predictions can be made to evaluate restoration options over a range of flow conditions. Earlier in Problem #7, we used the program to develop instream flow recommendations. In this exercise, we will apply the bedload transport options within WinXSPRO to assess the feasibility of spawning gravel placements.

Your assignment is as follows:

1. Load the WinXSPRO program and review the bedload transport options.

2. We will use the same cross-section data for this exercise as we did for Problem #7, and assume the D_{50} of the substrate is 50mm (coarse gravel).

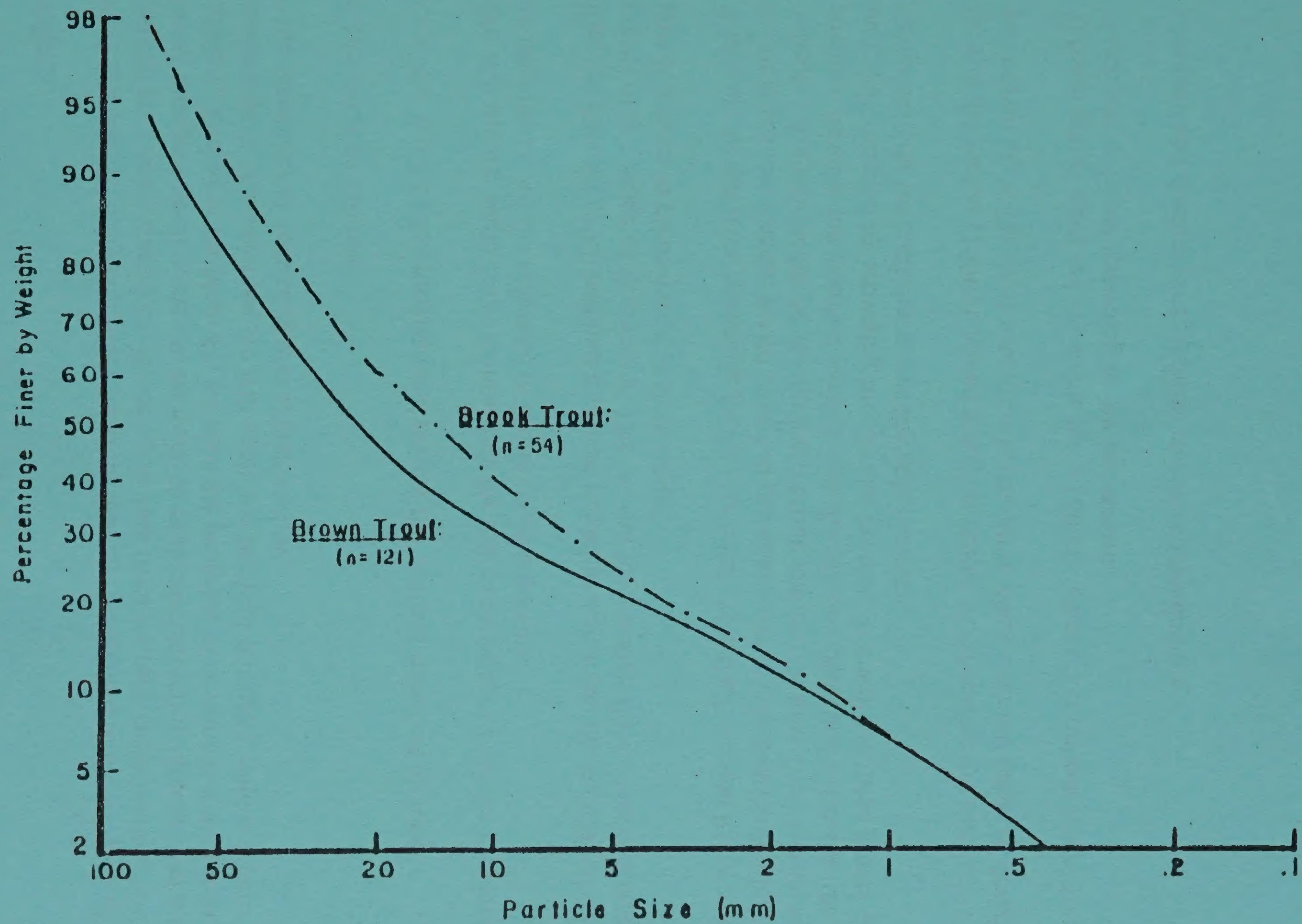
3. Run the Parker (1990) bedload transport model to determine the stability of this coarse gravel over a range of flows up to 150 cfs, our high design flow. Does this size of coarse gravel remain in place over this flow range?

4. While we do not have spawning gravel size criteria for the Colorado River cutthroat trout in our small test stream, we do have bed material particle size distribution information collected from the redds of similar sized brook and brown trout from similar nearby streams. Review the attached particle size distribution plots and determine the D_{50} of bed materials selected by spawning brooks and browns. We will use these gravel sizes as our design criteria for cutthroat spawning enhancement.

5. Re-run the Parker (1990) bedload transport model to determine the stability of the brook and brown D_{50}'s. Do these size gravels remain in place over our range of design flows?

6. If these gravel sizes are not stable up to 150 cfs, what other options might you consider to enhance cutthoat spawning in our test stream?

7. Compare and discuss your findings and recommendations.



Size distribution of bed material particles in Brown Trout and Brook Trout redds, Medicine Bow National Forest, Wyoming.

IN-CLASS PROBLEM #16
SHM Recommendations for the Santa Fe River
BLM Training Course 7000-12

The Problem:

In Problem #13 we applied the Stream Reach Inventory and Channel Stability Evaluation system on this section of the Santa Fe River below Santa Fe, N.M. Our analysis indicated this stream was highly embedded with sand and finer gravels, aggrading, overly widened, and very unstable. Mid-channel bars were common and large bed elements such as boulders caused extensive sediment deposition and in some cases, channel blow-outs. Historic land uses coupled with extensive water diversion have contributed substantially to this current condition, and should likely be the emphasis of any watershed restoration effort.

The objective of this exercise is to explore the possible role of SHM in the restoration of the Santa Fe River. Assuming that land use practices are being modified and efforts for hydrologic restoration are underway, complete the following steps:

1. Carefully review the seven Power Point photos of the Santa Fe and your SRI/CSE scorecard from earlier today.

2. Working in pairs, develop a list of up to several SHM treatments you feel may be effective in improving habitat quality throughout this reach. If you feel there is no role whatsoever for SHM here, say so and be ready to defend your position.

Goal Put cutthroat in the river
Objective is water temp 10-20°C, Thalweg ≥ 4 cm deep, 20% cover, substrate of clean gravel ≥ 5%, ≥ 30% pools (1.5 m deep); % fines < 20% in spawning habitat.

3. For the SHM treatments you feel may be beneficial, briefly review the cutthroat trout HSI model we worked with on Monday afternoon. Develop a list of HSI variables that may be influenced by your recommended treatments. For each affected variable, subjectively rate the degree of influence that may result from your SHM treatments. For in-class consistency, use "high", "moderate", and "low" as your ratings.

series of wing deflectors to create pools + clean gravel substrates

4. Present your recommendations and ratings.

5. Participate in a class discussion of possible SHM treatments and your justification for the recommendations you made.

IN-CLASS PROBLEM #1 - Answer Sheet
Building a Periodicity Chart and Habitat Matrix
BLM Training Course No. 7000-12

The Problem:

Periodicity charts and habitat matrices are commonly used in the aquatic habitat restoration field to summarize life history and habitat information for target fish species. These tools are especially useful when the investigator has little prior knowledge of the species or there are numerous species under consideration.

For this exercise, please do the following:

1. Review pages 1 to 7 in the Cutthroat Trout Habitat Suitability Index Model publication.

2. Using the attached form, build a periodicity table for the species. If you have management experience with the species, feel free to base your responses on that more site-specific information. If not, generalize.

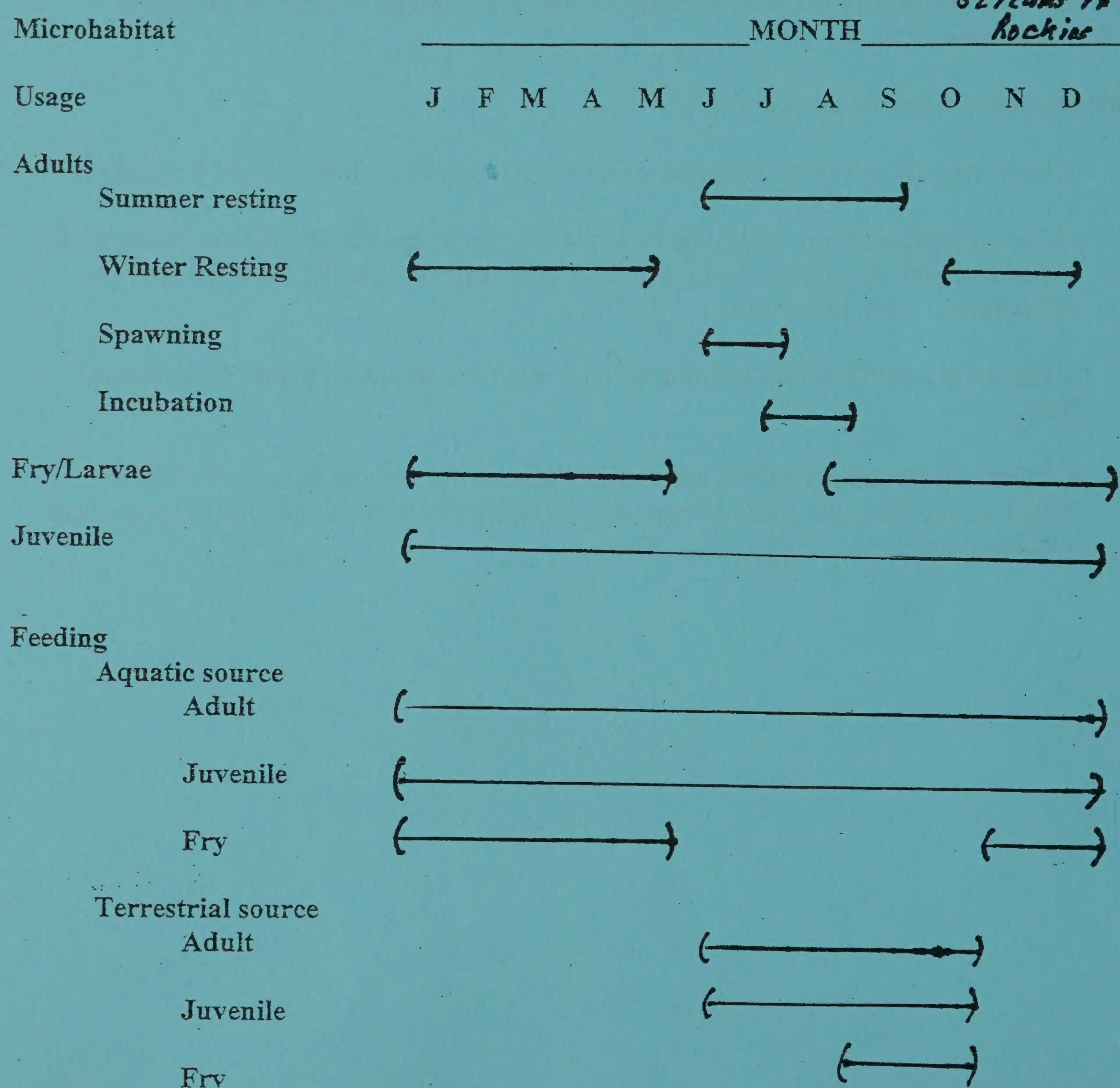
3. Using the attached form for guilding criteria, complete the habitat matrix for cutthroat trout.

4. Compare your cutthroat habitat matrix with those on the handout discussed in lecture. Which species does the cutthroat most closely resemble? Note: If you miss this one, there will be no recess!!! Rainbow trout.

PERIODICITY CHART

Species: Cutthroat Trout

System: ~~Southwest River~~ For headwater streams in Central Rockies



	Riverine						Lacustrine																				Turbidity tolerance		
	Habitat			Stream size			Habitat					Cover					Temperature[a]			Spawning[b]									
							Near-shore		Open-water																				
Species	Riffles, runs	Pools, eddies	Backwaters, bayous, oxbow lakes	Small (< 5 m); order: 1-3	Medium (5-30 m); order: 2-6	Large (> 30 m); order: 5+	Shallow (≤ 5 m)	Deep (> 5 m)	Surface (< 5 m)	Mid-water (5-15 m)	Deep (> 15 m)	Rocky substrate	Aquatic vegetation	Cut-banks	Logs, brush, debris piles	No special cover needs	Cold (< 20°C)	Cool (20-28°C)	Warm (> 28°C)	Free-drifting eggs, no substrate req.	Eggs deposited in or on rocky substrates; current required	Eggs deposited in or on rocky substrates; no current required	Eggs deposited on plants	Eggs deposited in holes, cavities	Eggs deposited in nests of mud, sand, or plant debris	Eggs deposited over a variety of substrates	Low (< 25 JTU)	Moderate (25-100 JTU)	High (> 100 JTU)
Cutthroat trout	X	X		X	X		X		X	X		X	X	X	X		X				X						X		

[a]Categories from Hokanson (1977)

[b]Categories from Balon (1975)

Guilding criteria for freshwater fishes.

IN-CLASS PROBLEM #2 - Answer Sheet
Slide Quiz Identifying Habitat Features
BLM Training Course No. 7000-12

Instructions:
You will be shown 10 photographs of streams and asked to name the identified habitat feature. Circle only one answer per question.

1. Name this mesohabitat: A. Riffle B. Step pool C. Dammed pool D. Cascade

2. According to Rosgen's classification, this channel type is an: A B C D E F G

3. This habitat feature is a: A. Glide B. Cut-off meander C. Braided channel D. Pool

4. This type of ice is: A. Anchor B. Shelf C. Frazil D. Cube

5. Name this mesohabitat: A. Mid-channel pool B. Lateral scour pool C. Cascade D. High gradient riffle E. Low gradient riffle

6. Name this mesohabitat: A. Backwater eddy B. Low gradient riffle C. Cut-off meander D. Braided channel E. Glide

7. Name this mesohabitat: A. Low gradient riffle B. Cascade C. Waterfall D. Run

8. A pool formed here would be a: A. Lateral scour pool B. Dammed pool C. Plunge pool D. Mid-channel pool E. Run

9. A pool formed here would be a: A. Lateral scour pool B. Dammed pool C. Plunge pool D. Mid-channel pool E. Run

10. Name this mesohabitat: A. High gradient riffle B. Run C. Low gradient riffle D. Pool E. Cascade

IN-CLASS PROBLEM #3 - *Answer Sheet*
Selecting a Reference Reach
BLM Training Course 7000-12

The Problem:

Selecting a suitable reference reach can be a challenging and thought provoking undertaking. In this exercise, we will be comparing the characteristics of five Clark Fork River test reaches with those of three possible reference reaches. Your objective is to select a reference reach for each of the five test reaches based upon the photographs and data provided. In this case, the "disturbance" was water quality related, so no water quality data are presented.

Your assignment is as follows:

1. Review the Power Point photographs of the eight reaches, noting valley, channel, and habitat characteristics.

2. Review the attached data plots which compare the test and reference reaches.

3. Develop a "decision matrix" to help you compare and contrast the reaches. An example matrix is provided below.

4. Select a reference for each of the five Clark Fork test reaches.

5. Present, discuss and defend your choices.

RATING FOR EACH CHARACTERISTIC

	Big Hole	Flint Ck	Rock Ck
	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12	1 2 3 4 5 6 7 8 9 10 11 12
CFR1(Galen)			
CFR2(DL)			
CFR3(GC)	This is a "subjective" exercise.		
CFR4(Clint)	There are not necessarily right or wrong		
CFR5(Turah)	answers.		

Ratings: 1 = Similar 2 = Somewhat similar 3 = Not similar

Characteristics: 1 = Valley; 2 = Channel; 3 = Habitat; 4 = Ave. Ann. Flow; 5 = Monthly Flows
6 = Basin area; 7 = Main ch. length; 8 = Channel elev.; 9 = Stream gradient;
10 = Total roads density; 11 = % altered channel; 12 = Ratio irrigated land

IN-CLASS PROBLEM #4 – Answer Sheet
Applying SSTemp for Limiting Factor Analysis
BLM Training Course No. 7000-12

The Problem:

As discussed in class, SSTemp is an easily applied model that can be used to evaluate water temperature as a potential limiting factor for a target species and to investigate the influence of possible management actions. In this exercise, you will be predicting mean daily and maximum water temperatures in the Middle Rio Grande from Albuquerque downstream 12.3 miles to Isleta based upon a given set of hydrologic and climatologic conditions. Your target species will be the Rio Grande silvery minnow.

Your assignment is as follows:

1. Working in pairs, load the SSTemp software and review the Power Point photos.

2. Input the attached data on the SSTemp program data screen.

3. Run the model to determine the predicted mean and maximum daily water temperature at Isleta on September 3.

4. Based upon the attached hypothetical water temperature suitability index plot for Rio Grande silvery minnow, how has temperature suitability changed between Albuquerque and Isleta? Mean temp remains in optimum range.

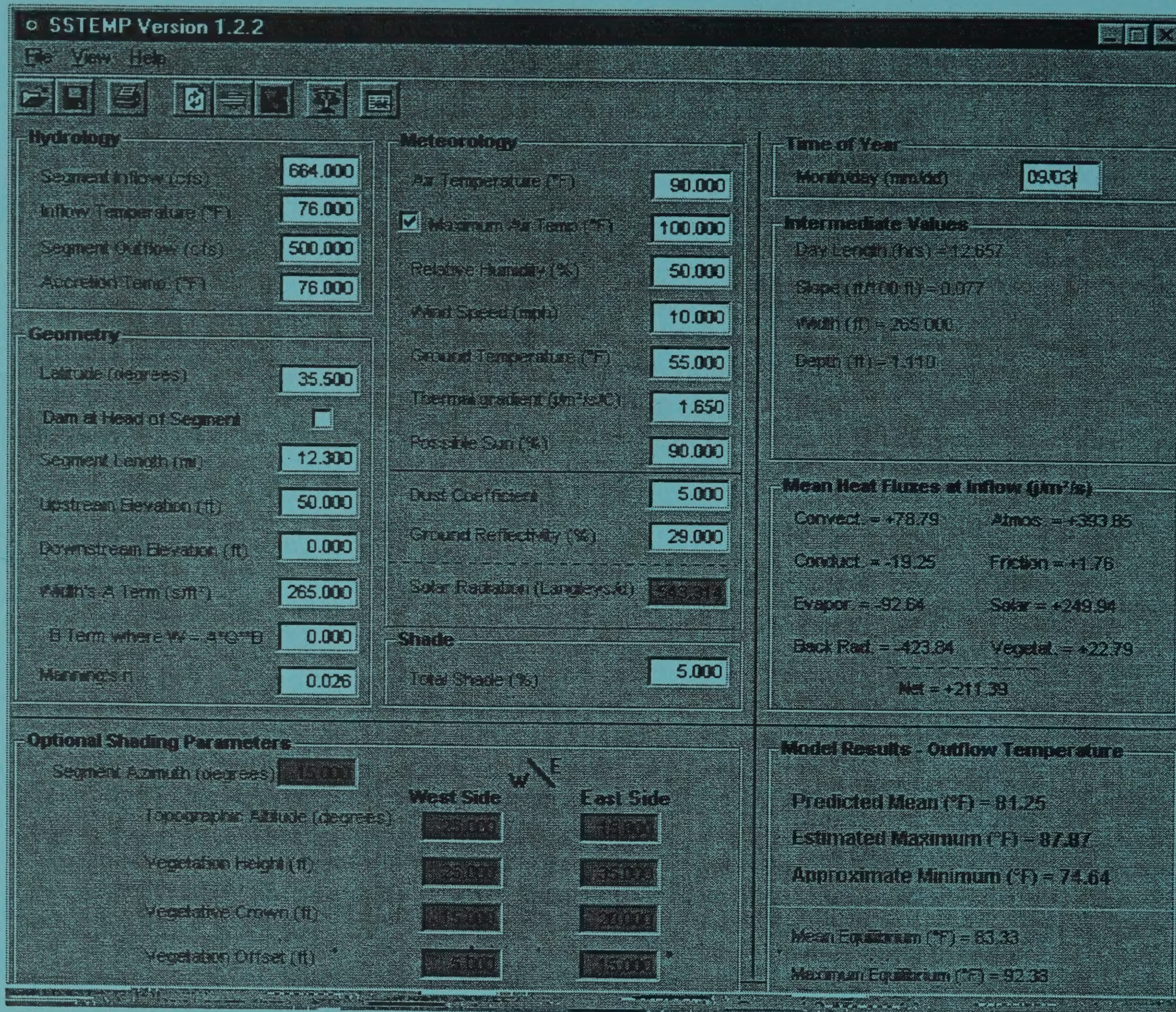
5. For the climatologic conditions on which this problem is based, do you consider water temperature to be a limiting factor for the minnow? No

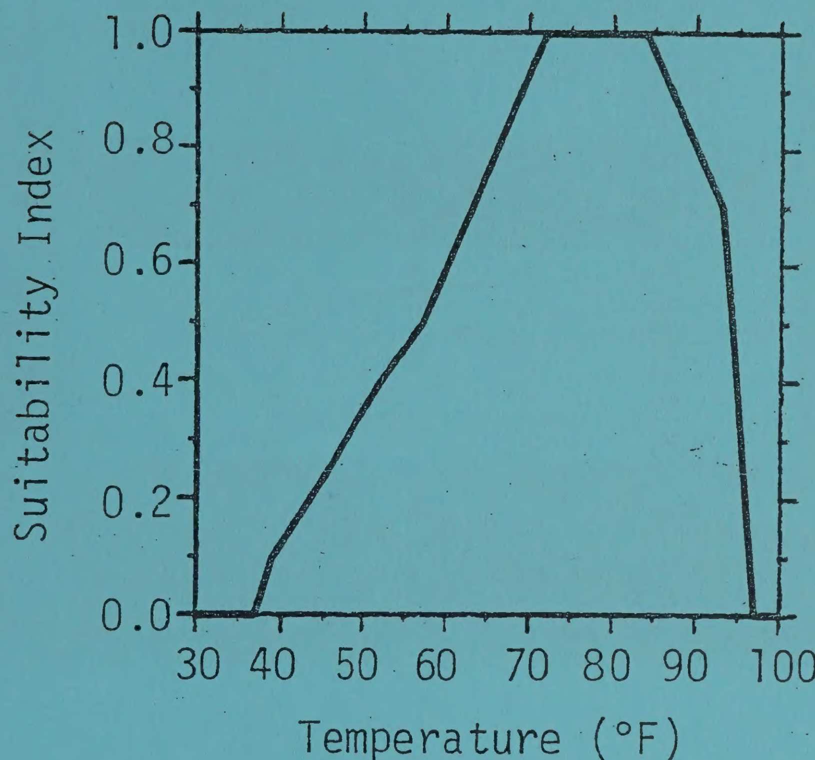
6. Total shade has been set at 5%. "Game" with this potential management variable. How are mean and maximum temperatures affected by increasing shading to 25 and 50%? How does this affect temperature suitability? Little effect.

7. On the Tool Bar, go to the View Flow/Distance Matrix and inspect the various graphs. If due to drought flow were reduced 67% to 221 cfs, how is mean temperature suitability for the minnow affected? Remains at high end of optimum range.

8. If this channelized stream segment were to be re-constructed to increase meandering, thereby increasing segment length to 16.0 miles, how is mean temperature suitability for the minnow affected? Remains near high end of optimum range.

9. Discuss your results and conclusions.


SSTEMP Version 1.2.2
File View Help
Hydrology
Segment Inflow (cfs) 664.000
Inflow Temperature (°F) 76.000
Segment Outflow (cfs) 500.000
Accretion Temp. (°F) 76.000
Geometry
Latitude (degrees) 35.500
Dam at Head of Segment
Segment Length (mi) 12.300
Upstream Elevation (ft) 50.000
Downstream Elevation (ft) 0.000
Width's A Term (s/ft²) 265.000
B Term where W = A*Q**B 0.000
Manning's n 0.026
Meteorology
Air Temperature (°F) 90.000
Maximum Air Temp (°F) 100.000
Relative Humidity (%) 50.000
Wind Speed (mph) 10.000
Ground Temperature (°F) 55.000
Thermal gradient (j/m²/s/C) 1.650
Possible Sun (%) 90.000
Dust Coefficient 5.000
Ground Reflectivity (%) 29.000
Solar Radiation (Langleys/d)
Shade
Total Shade (%) 5.000
Time of Year
Month/day (mm/dd) 09/03
Intermediate Values
Day Length (hrs) = 12.657
Slope (ft/100 ft) = 0.077
Width (ft) = 265.000
Depth (ft) = 1.110
Mean Heat Fluxes at Inflow (j/m²/s)
Convect. = +78.79
Atmos. = +393.85
Conduct. = -19.25
Friction = +1.76
Evapor. = -92.64
Solar = +249.94
Back Rad. = -423.84
Vegetat. = +22.79
Net = +211.39
Optional Shading Parameters
Segment Azimuth (degrees) 15.000
W E
West Side
East Side
Topographic Altitude (degrees) 25.000 15.000
Vegetation Height (ft) 25.000 35.000
Vegetative Crown (ft) 15.000 20.000
Vegetation Offset (ft) 5.000 15.000
Model Results - Outflow Temperature
Predicted Mean (°F) = 81.25
Estimated Maximum (°F) = 87.87
Approximate Minimum (°F) = 74.64
Mean Equilibrium (°F) = 83.33
Maximum Equilibrium (°F) = 92.38



1.0
0.8
0.6
0.4
0.2
0.0
Suitability Index
30
40
50
60
70
80
90
100
Temperature (°F)

SSTEMP (1.2.2) Matrix

Mean Daily Temperatures (°F)

Q (cfs)	X - Distance (mi) 0.001	2.500	5.000	7.500	10.000
16.667	70.00	76.25	79.66	81.43	82.34
33.333	70.00	74.10	77.05	79.11	80.53
50.000	70.00	73.14	75.62	77.56	79.05
66.667	70.00	72.58	74.72	76.49	77.94
83.333	70.00	72.20	74.10	75.71	77.08

1 Graph by Q

2 Graph by X

Maximum Daily Temperatures (°F)

Q (cfs)	0.001	2.500	5.000	7.500	10.000
16.667	77.06	82.04	84.76	86.18	86.90
33.333	75.97	79.44	81.93	83.67	84.88
50.000	75.37	78.10	80.26	81.94	83.24
66.667	74.96	77.23	79.13	80.69	81.97
83.333	74.64	76.61	78.30	79.75	80.97

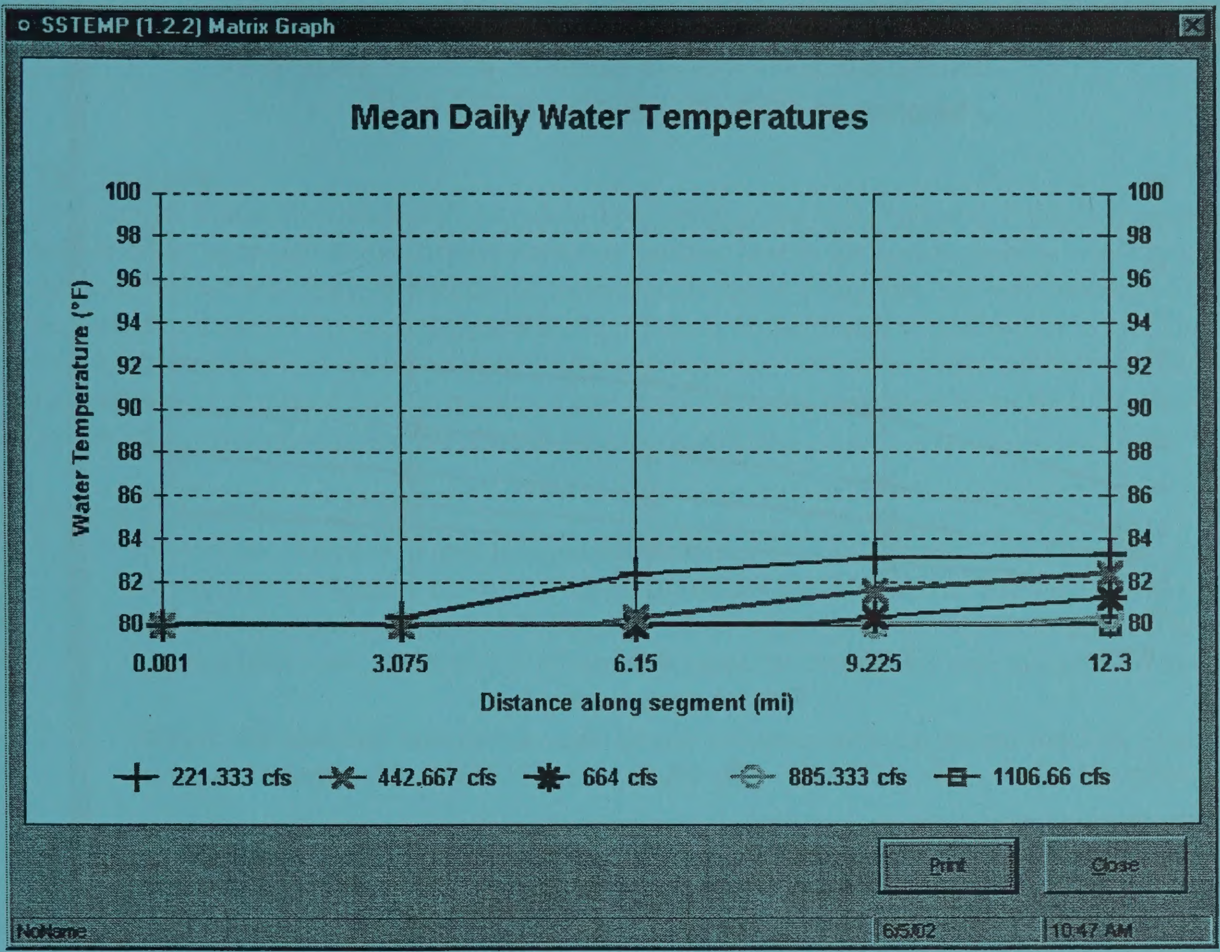
3 Graph by Q

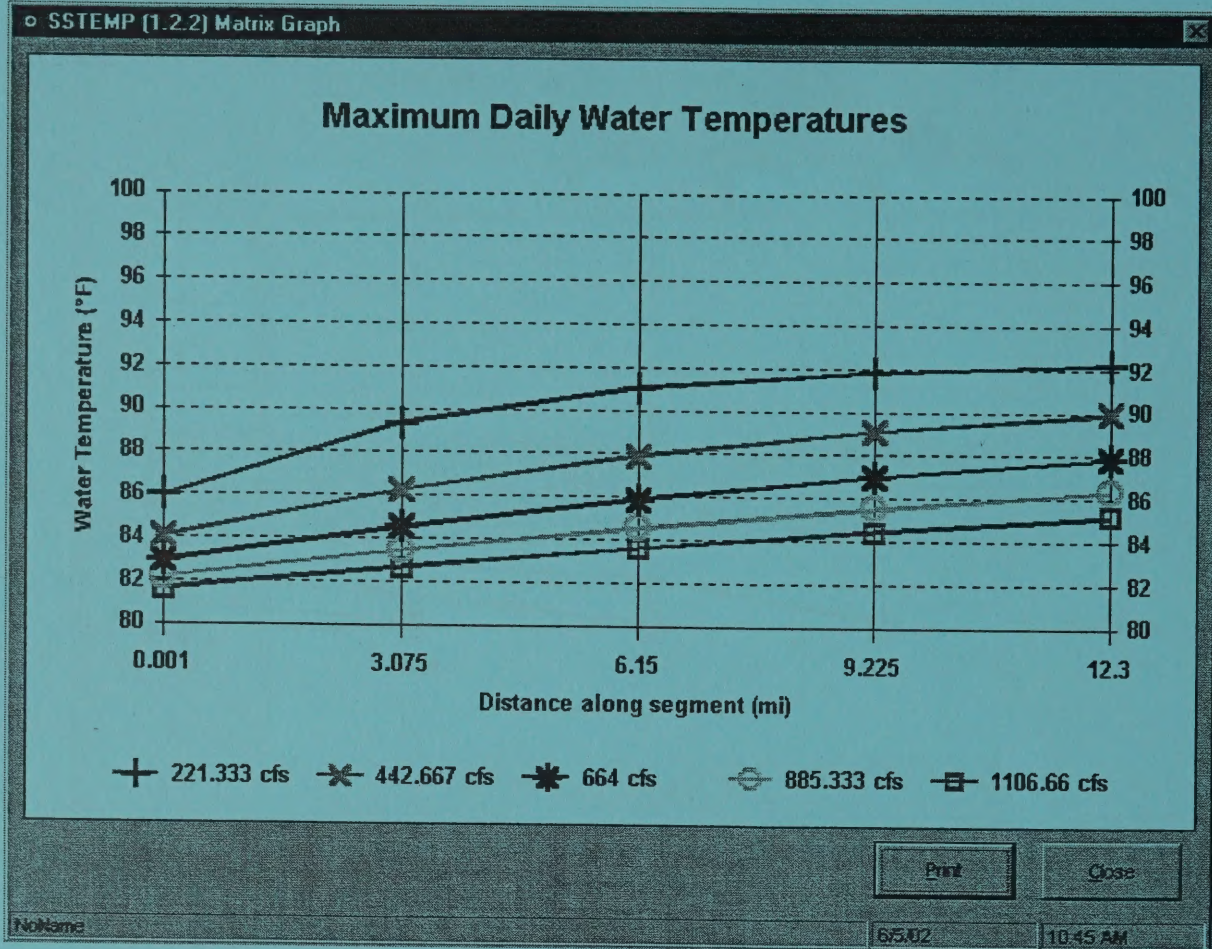
4 Graph by X

Enter 5 inflows and 5 distances along the segment to compute temperatures.

Print Form   Close

NoName   6/5/02   11:31 AM


SSTEMP (1.2.2) Matrix Graph
Mean Daily Water Temperatures
Water Temperature (°F)
100
98
96
94
92
90
88
86
84
82
80
0.001
3.075
6.15
9.225
12.3
Distance along segment (mi)
221.333 cfs
442.667 cfs
664 cfs
885.333 cfs
1106.66 cfs
Print
Close
NoName
6/5/02
10:47 AM


SSTEMP (1.2.2) Matrix Graph
Maximum Daily Water Temperatures
Water Temperature (°F)
100
98
96
94
92
90
88
86
84
82
80
0.001
3.075
6.15
9.225
12.3
Distance along segment (mi)
221.333 cfs
442.667 cfs
664 cfs
885.333 cfs
1106.66 cfs
Print
Close
NoName
6/5/02
10:45 AM

IN-CLASS PROBLEM #5 – Answer Sheet
Identifying Potential Limiting Factors Using HSI Models
BLM Training Course No. 7000-12

The Problem:

The Habitat Suitability Index (HSI) models developed by the U.S. Fish and Wildlife Service are a user-friendly approach to identifying potential limiting factors for aquatic habitat restoration. In this exercise we will apply the cutthroat trout model, one of many that has been developed for terrestrial and aquatic species nationwide. Application of the model will allow us to identify for which life stage habitat quality is potentially most limiting, as well as those habitat variables most responsible for impaired habitat quality. Once these variables have been identified, concise yet quantifiable restoration objective statements can be written.

Your assignment is as follows:

1. Review the Cutthroat Trout HSI manual provided in your handouts, paying particular attention to a) Figure 1 on page 8 which illustrates the relationship between model variables, components, and HSI; b) pages 11-17 which present the suitability curves for each variable; and, c) pages 22-26 which present the component and overall HSI models.

2. Review the attached sample data sets for our reference and test stream reaches. Please be sure you understand how the suitability index (SI) values for each variable were obtained.

3. Working in pairs, calculate the component (adult, juvenile, fry, embryo, and other) and species HSI scores for the reference and test reaches using the riverine models. Calculate the species HSI using the equal component value method on page 24. **To save time, let's have half the class work with the reference data and the other half with the test data. We'll post all scores on the board.**

4. For the test reach, identify which life stage(s) is potentially most limited by habitat quality based upon the component scores. Also, for all life stages, identify which habitat variables are most limiting.

5. Prioritize the habitat variables identified in Step 4, and for the top 3 (those you feel are most limiting and which can be managed for), write concise, quantitative restoration objective statements.

6. Present, discuss, and defend your findings.

Component	Reference	Test
C_A	0.95	0.37
C_J	1.00	0.37
C_F	0.97	0.55
C_E	1.00	0.40
C_O	0.96	0.40
Species HSI	0.98	0.37

		Reference		Test	
		Data set		Data set	
Variable		Data	SI	Data	SI
Max. temperature (°C)	V_1	14	1.0	16	1.0
Max. temperature (°C)	V_2	12	1.0	17	0.4
Min. dissolved O_2 (mg/l)	V_3	9	1.0	6	0.42
Ave. depth (cm)	V_4	25	0.9	18	0.6
Ave. velocity (cm/s)	V_5	30	1.0	20	0.57
% cover	V_6	20	A 0.95 J 1.0	10	A 0.65 J 0.92
Ave. gravel size (cm)	V_7	4	1.0	2.5	1.0
Dom. substrate size (cm)	V_8	15	1.0	8	0.7
Dom. substrate class	V_9	A	1.0	B	0.6
% pools	V_{10}	55	1.0	10	0.46
% Alloch. vegetation	V_{11}	225	1.0	200	1.0
% bank vegetation	V_{12}	95	1.0	40	0.5
Max. pH	V_{13}	7.1	1.0	7.2	1.0
% Ann. base flow	V_{14}	37	0.8	25	0.5
Pool class	V_{15}	A	1.0	C	0.3
% fines (A)	V_{16}	5	1.0	20	0.5
% fines (B)	V_{16}	15	0.9	30	0.6
% shade	V_{17}	60	1.0	60	1.0

Pool development + shading would be high priorities.

IN-CLASS PROBLEM #6 - *Answer Sheet*
Applying IHA and RVA
BLM Training Course No. 7000-12

The Problem:

The Indicators of Hydrologic Alteration (IHA) procedure can be used to compare a river's stream flow regime before and after a water management change, thereby quantifying the magnitude and direction of change for 32 parameters considered to be of ecological significance. The Range of Variability Approach (RVA) can then be applied to establish target ranges for each of the 32 flow parameters, which if met, will help to restore a regime more similar to the pre-impact condition. The degree to which the RVA target range is not attained is considered a measure of hydrologic alteration. In this exercise, we will apply IHA and RVA to assess the degree of hydrologic alteration which has occurred as a result of the construction of Cochiti dam on the Middle Rio Grande in the early 1970's, 50 miles upstream of Albuquerque, NM. Our pre-impact period-of-record will be 1942 - 1970, while our post-impact period will be 1975 - 1999.

Your assignment is as follows:

1. Load the CD containing the program and follow the instructions on the attached page to run your analysis.

2. From the mass of results you will obtain, locate and review a) the mean monthly flow alteration plot; b) the IHA Parametric Scorecard table; and c) the IHA Parametric RVA Scorecard table.

3. Following your review of results, answer the following:
   a) Are mean monthly flows higher or lower since Cochiti dam was built? *Higher*
   b) Are days of zero flow more or less common since Cochiti was built? *Less*
   c) Is the date of maximum flow earlier or later in the year since Cochiti? *Earlier*
   d) Which month has seen the greatest flow increase (in cfs) since Cochiti? *July*
   e) Are flows generally more or less variable since Cochiti? *Less*
   f) Which Parameter Group has been most affected by Cochiti? *Parameter Group #2*
   g) Which month has the widest RVA target flow range? *May*
   h) For which month have post-Cochiti flows best met the RVA targets? *August*
   i) For which month have post-Cochiti flows least met the RVA targets? *January*
   j) Have post-Cochiti flows best met the "minimum" or "maximum" RVA targets? *Maximum*

4. Discuss the possible biological significance of these hydrologic alterations for the Rio Grande silvery minnow.

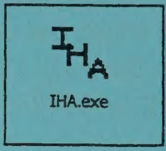
Indicators of Hydrologic Alteration
Attachment to Problem Set 6

Load CD into Drive. Double Click IHA folder
"Unzip" IHA onto your computer.

IHA Program Setup:
Double-click the "**setup**" program to load IHA program.
(It is highly recommended you put this program right in your root directory and do not use spaces or long names as the directory name; i.e. C:/IHA

Next, copy "**Batchfor.exe**" from the CD to the directory where you set up IHA. This is a patch for a bug found.

Open **IHA.**



Data file we will use is **RGAlbdis.dat** located in the IHA folder on the CD.
Copy this file to your directory (makes it easier to use). This file is already in IHA format.

From pull–down menu, run "Wizard" off the **IHA Analysis.**

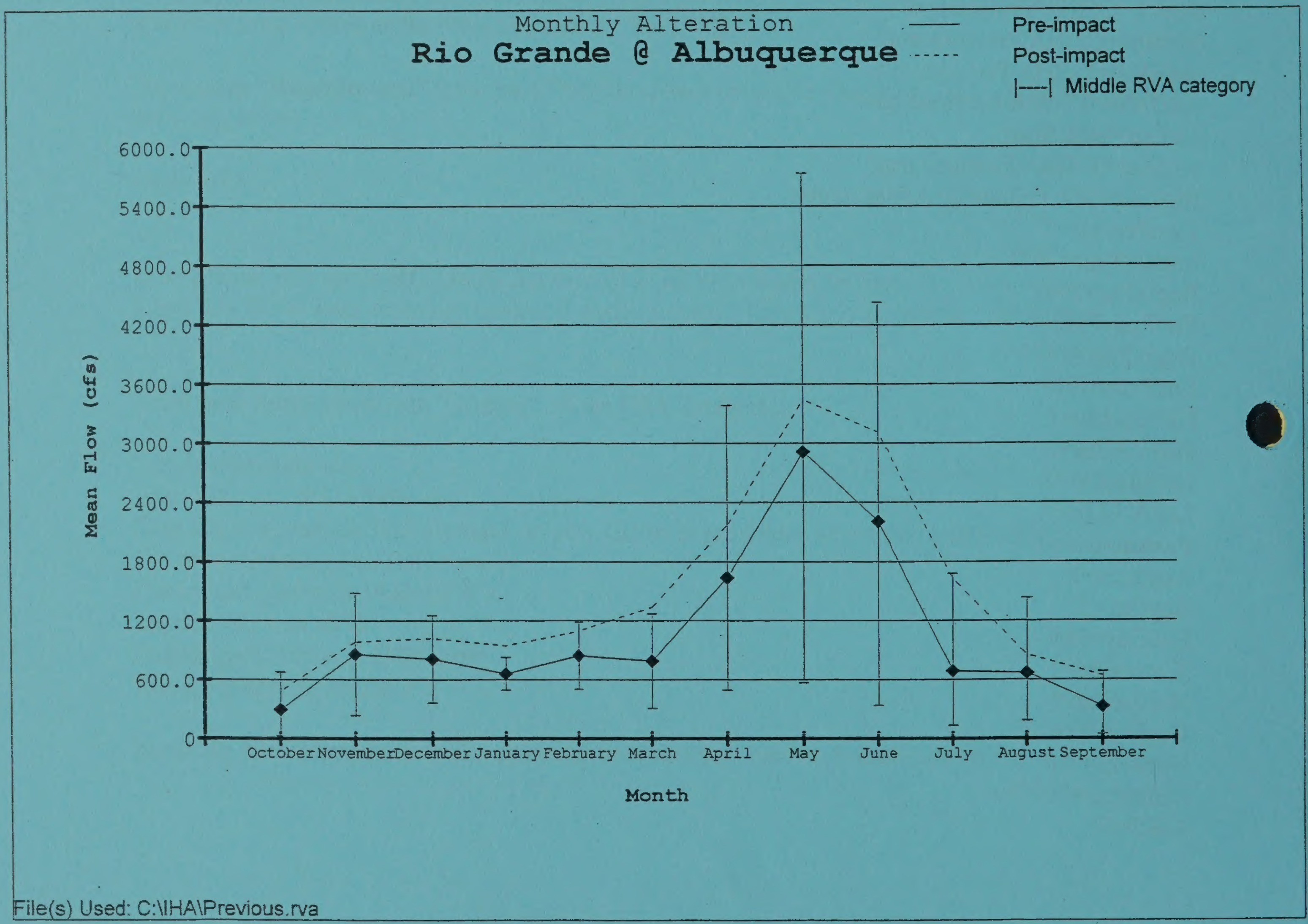
Your parameters are:
Data file is : **RGAlbdis.dat**
Data file is already in IHA format (on your CD or in the folder where you loaded IHA).
We are comparing two time periods.
Pre-Impact period is **1942-1970**
Impact year was **1971**
Post-Impact Period is **1975-1999**
Run a parametric analysis

Name the files whatever you like (keeping them short) or use the default filenames.

Previous.Par file

(And/or Myparameters.par for parametric test)

```
&initial
infile='C:\IHA\RGAlbdis.dat'
outscore='C:\IHA\Previous.sco'
outpct='C:\IHA\Previous.pct'
outsum='C:\IHA\Previous.ann'
outRVA='C:\IHA\Previous.rva'
outBAW='C:\IHA\Previous.baw'
outLsq='undefined'
outMsg='C:\IHA\Previous.msg'
BigTitle='Rio Grande @ Albuquerque'
TwoPeriods=T
ImpactYear=1971
BeginPre=1942
EndPre=1970
BeginPost=1975
EndPost=1999
HiPulseLvl=1.
HiRVAlim=1.
LoPulseLvl=1.
LoRVALim=1.
Parametric=T
Absolute=F
BegDay=1
EndDay=366
Watershed=1
Normalize=1
BegWatrYr=275
Nmissing=10
Rmissing=999999
MKS=F
/
```


Monthly Alteration
Rio Grande @ Albuquerque
Pre-impact
Post-impact
|----| Middle RVA category
6000.0
5400.0
4800.0
4200.0
3600.0
3000.0
2400.0
1800.0
1200.0
600.0
0
Mean Flow (cfs)
October
November
December
January
February
March
April
May
June
July
August
September
Month
File(s) Used: C:\IHA\Previous.rva

IHA Parametric Scorecard

Rio Grande @ Albuquerque

Pre-impact period: 1942-1970 (29 years) Post-impact period: 1975-1999 (25 years)

	MEAN		COEFF. of VAR.		DEVIATION FACTOR		DEV. of C.V.	
	Pre	Post	Pre	Post	Magnitude	%	Magnitude	%
Parameter Group #1								
October	296.4	485.6	1.29	.82	189.3	63.9	-.47	-36.7
November	859.9	985.4	.73	.48	125.5	14.6	-.25	-33.8
December	811.1	1021.3	.55	.41	210.2	25.9	-.14	-25.3
January	660.9	946.8	.25	.37	285.9	43.3	.12	49.0
February	844.7	1094.8	.40	.65	250.1	29.6	.25	61.6
March	791.2	1335.5	.61	.48	544.3	68.8	-.13	-21.2
April	1638.5	2169.4	1.07	.65	530.9	32.4	-.42	-39.1
May	2915.2	3441.5	.97	.53	526.3	18.1	-.44	-45.5
June	2206.7	3111.7	1.01	.64	905.1	41.0	-.37	-36.6
July	690.4	1624.7	1.43	.93	934.3	135.3	-.50	-34.9
August	670.3	855.4	1.14	.78	185.1	27.6	-.36	-31.4
September	327.4	640.5	1.09	.66	313.1	95.6	-.43	-39.5
Mean |%| change					49.7		37.9	
Parameter Group #2								
1-day minimum	38.0	161.3	2.14	1.03	123.3	324.8	-1.11	-52.1
3-day minimum	43.9	167.9	2.11	.96	124.0	282.6	-1.15	-54.4
7-day minimum	55.2	187.9	2.00	.89	132.7	240.3	-1.10	-55.2
30-day minimum	89.9	267.5	1.47	.67	177.6	197.5	-.81	-54.9
90-day minimum	229.9	450.1	.70	.46	220.2	95.8	-.24	-34.6
1-day maximum	5837.9	5142.8	.76	.40	-695.1	-11.9	-.36	-47.9
3-day maximum	5183.9	4964.4	.75	.40	-219.5	-4.2	-.34	-46.0
7-day maximum	4749.2	4755.4	.73	.42	6.2	.1	-.32	-43.1
30-day maximum	3787.7	4174.9	.78	.45	387.2	10.2	-.33	-42.2
90-day maximum	2548.4	3245.1	.80	.48	696.7	27.3	-.31	-39.4
Number of zero days	7.86	.36	2.00	4.46	-7.50	-95.42	2.46	122.82
Base flow	.04	.13	1.55	.90	.08	191.19	-.65	-42.22
Mean |%| change					123.5		52.9	
Parameter Group #3								
Date of minimum	252.3	257.6	.10	.12	5.3	2.9	.02	20.8
Date of maximum	161.9	149.4	.17	.11	12.5	6.9	-.07	-38.1
Mean |%| change					4.9		29.4	
Parameter Group #4								
Low pulse count	8.7	3.5	.61	1.27	-5.2	-59.7	.66	107.4
Low pulse duration	8.2	4.6	.74	1.31	-3.6	-43.4	.57	76.9
High pulse count	2.5	3.0	.98	.90	.5	20.8	-.08	-8.3
High pulse duration	10.3	25.9	1.25	.96	15.6	151.5	-.28	-22.8
Mean |%| change					68.8		53.8	

The low pulse threshold is 241.25

The high pulse level is 2653.81

	MEAN		COEFF. of VAR.		DEVIATION FACTOR		DEV. of C.V.	
Parameter Group #5								
Rise rate	159.3	134.8	.72	.27	-24.5	-15.4	-.45	-62.2
Fall rate	-141.6	-122.5	-.78	-.31	19.0	-13.4	.47	-60.5
Number of reversals	134.5	133.2	.10	.08	-1.3	-1.0	-.03	-25.6
Mean |%| change					9.9		49.5	

IHA Parametric RVA Scorecard

Rio Grande @ Albuquerque

	Pre-impact period: 1942-1970				Post-impact period: 1975-1999				RVA TARGETS		⊥ HYDROLOGIC ALTERATION
		Std.	Range Limits			Std.	Range Limits				
	Means	Dev.	Low	High	Means	Dev.	Low	High	Low	High	
Parameter Group #1											
October	296.4	1.3	.0	1403.5	485.6	.8	38.4	1801.6	28.92	678.46	.29
November	859.9	.7	66.1	2211.0	985.4	.5	144.8	2302.3	236.25	1483.52	.28
December	811.1	.5	270.4	2053.5	1021.3	.4	480.4	2276.5	365.26	1256.94	.10
January	660.9	.2	391.6	1100.0	946.8	.4	486.4	2158.7	496.12	825.75	-.61
February	844.7	.4	453.3	2145.5	1094.8	.7	589.8	3562.1	504.24	1185.15	.01
March	791.2	.6	167.2	2102.9	1335.5	.5	480.0	2790.3	309.74	1272.66	-.25
April	1638.5	1.1	54.7	8570.7	2169.4	.6	137.2	6342.6	493.92	3385.31	.04
May	2915.2	1.0	112.0	11236.1	3441.5	.5	148.3	6203.2	569.19	5734.64	.30
June	2206.7	1.0	11.6	6993.0	3111.7	.6	336.4	6113.0	339.55	4427.62	.24
July	690.4	1.4	.0	4182.9	1624.7	.9	333.4	5438.7	133.08	1679.89	.16
August	670.3	1.1	28.4	3687.1	855.4	.8	278.3	3451.9	184.13	1434.72	.42
September	327.4	1.1	12.9	1614.5	640.5	.7	69.6	1554.0	46.85	684.01	.03
Parameter Group #2											
1-day minimum	38.0	2.1	.0	395.0	161.3	1.0	.0	515.0	.00	119.21	-.44
3-day minimum	43.9	2.1	.0	433.0	167.9	1.0	.0	532.3	.00	136.71	-.44
7-day minimum	55.2	2.0	.0	503.3	187.9	.9	.0	560.3	.00	165.46	-.40
30-day minimum	89.9	1.5	.0	528.0	267.5	.7	13.2	606.1	3.36	222.52	-.23
90-day minimum	229.9	.7	5.2	582.0	450.1	.5	8.1	758.6	69.78	390.09	-.48
1-day maximum	5837.9	.8	1080.0	20600.0	5142.8	.4	1640.0	8650.0	1413.76	10262.10	.38
3-day maximum	5183.9	.7	970.0	16400.0	4964.4	.4	1466.7	8400.0	1306.55	9061.28	.38
7-day maximum	4749.2	.7	901.3	13628.6	4755.4	.4	1138.1	8172.9	1259.61	8238.79	.33
30-day maximum	3787.7	.8	670.5	11791.7	4174.9	.5	593.3	7552.3	827.63	6747.73	.16
90-day maximum	2548.4	.8	555.9	9062.6	3245.1	.5	556.7	5886.4	935.35	4578.35	.10
Number of zero days	7.9	2.0	.0	68.0	.4	4.5	.0	8.0	.00	23.58	.12
Base flow	.0	1.5	.0	.3	.1	.9	.0	.4	.00	.11	-.35
Parameter Group #3											
Date of minimum	252.3	.1	172.0	319.0	257.6	.1	151.0	345.0	226.68	278.01	-.15
Date of maximum	161.9	.2	39.0	333.0	149.4	.1	53.0	231.0	133.90	189.89	.39
Parameter Group #4											
Low pulse count	8.7	.6	.0	20.0	3.5	1.3	.0	16.0	3.37	14.08	-.53
Low pulse duration	8.2	.7	.0	26.7	4.6	1.3	.0	29.0	2.14	14.27	-.29
High pulse count	2.5	1.0	.0	9.0	3.0	.9	.0	11.0	.05	4.91	.01
High pulse duration	10.3	1.2	.0	50.0	25.9	1.0	.0	79.0	.00	23.15	-.23

The low pulse threshold is 241.25
The high pulse threshold is 2653.81

	Means	Std. Dev.	Low	High	Means	Std. Dev.	Low	High	Low	High	HYDROLOGIC ALTERATION
Parameter Group #5											
Rise rate	159.3	.7	50.7	657.9	134.8	.3	66.7	214.1	90.75	273.66	.33
Fall rate	-141.6	-.8	-619.0	-41.6	-122.5	-.3	-194.5	-55.3	-251.30	-86.15	.16
Number of reversals	134.5	.1	92.0	159.0	133.2	.1	109.0	151.0	120.44	148.60	.05

⊥ (Observed − Expected)/Expected, where Observed is # of years in post-impact period that fell within RVA Target range; and Expected is the count of years for which the value is expected to fall within range. If norm[illegible] distributed, 68% of years "expected". +HA means Observed > Expected; −HA means Observed < Exp[illegible]ed

IN-CLASS PROBLEM #7 - Answer Sheet
WinXSPRO Applications for Instream Flow Analysis
BLM Training Course No. 7000-12

The Problem:

As we've discussed, WinXSPRO is a user-friendly program which allows you to model the hydraulics of single stream cross-sections over a range of flow conditions. These capabilities allow the program to be used for some instream flow applications. In this exercise, you will model a cross-section from a small cutthroat trout stream and use the output to develop instream flow recommendations.

Your assignment is as follows:

1. Load the WinXSPRO program and review.

2. Input the cross-section data provided on the attached page. These data were collected at water stage = 1.8 ft.

3. Run the program using a constant slope of 0.003 and a Manning's n of 0.04 for low stage and 0.03 for high stage. The range of water stage you should model are from 0.5 ft up to 2.4 ft.

4. Once you've obtained your model results, check your output using the following field measured flow values: 1.2 ft stage = 26 cfs; 1.7 ft stage = 70 cfs; 1.8 ft stage = 78 cfs. If your output is more than 5-10% different than these values, better double-check things.

5. Plot wetted perimeter against flow and identify the inflection point. The flow at the point of inflection is commonly recommended as a late season baseflow because it avoids the flow range having the greatest rate of habitat loss and it protects a high percentage of the available rearing (food and cover) habitat. $Q_{IF} = 25$ cfs

6. Suitable cutthroat trout spawning habitat in smaller streams has been described as having a water velocity of 1.0 to 2.0 ft/s, a water depth of at least 0.6 ft, and a gravel substrate. Assuming the substrate is gravel, inspect your hydraulic output table and identify the flow for which mean velocity and depth first meet these criteria. This flow can serve as a spawning and incubation recommendation. $Q_{IF} = 25$ cfs

7. Compare and discuss your recommendations.

Cross Section Data for Problem Set

Location (ft)	Tape Height (Ft)
0	0.3
1	0.92
2	1.5
3.5	1.54
5	1.66
6.5	1.77
8	1.83
9.5	1.88
11	1.92
12.5	2.00
14	2.03
15.5	2.05
17	2.09
18.5	2.11
20	2.13
21.5	2.24
23	2.45
24.5	2.64
26	2.72
27	1.78
27.4	0.92
28	0.3

*****************************WinXSPRO*********************************

C:\PROGRAMS\WXSPRO20\WSC.OUT

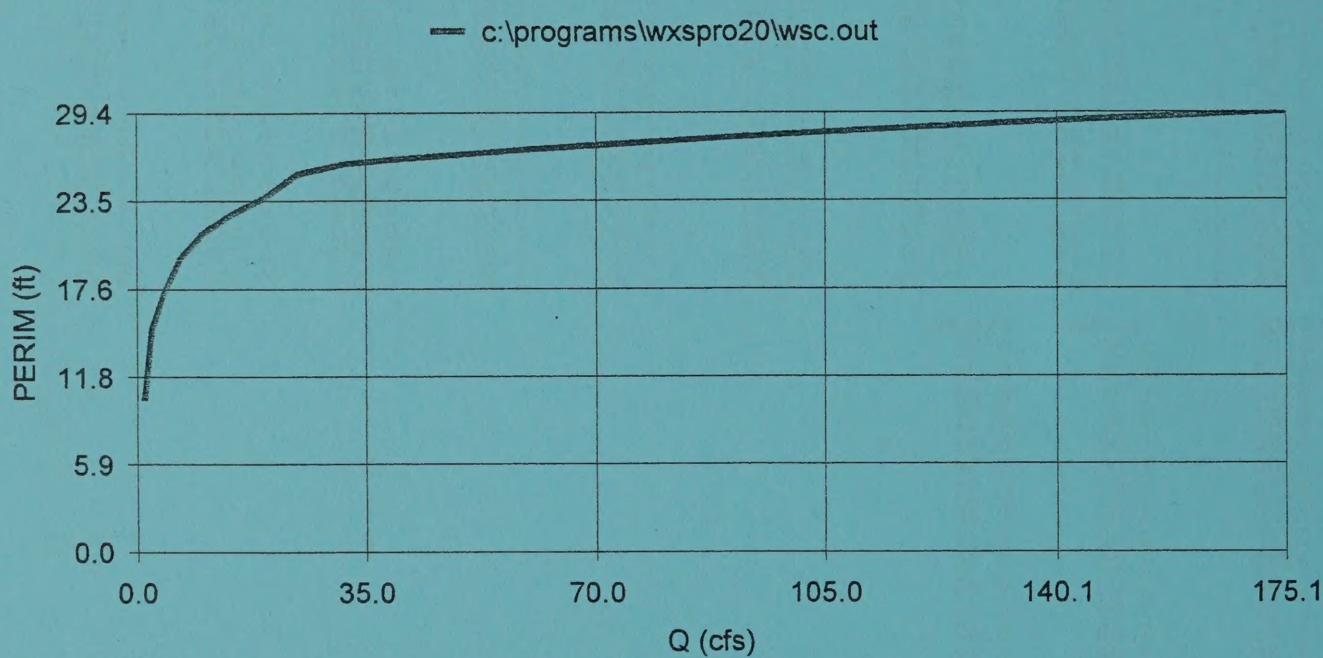
Input File:	C:\PROGRAMS\WXSPRO20\WSC.DAT
Run Date:	06/05/02
Analysis Procedure:	Hydraulics
Cross Section Number:	1
Survey Date:	7/25/98

Subsections/Dividing stations
A

Resistance Method:	Manning's n
SECTION	A
Low Stage n	0.040
High Stage n	0.030

STAGE (ft)	#SEC	AREA (sq ft)	PERIM (ft)	WIDTH (ft)	R (ft)	DHYD (ft)	SLOPE (ft/ft)	n	VAVG (ft/s)	Q (cfs)
0.50	T	1.89	10.40	10.17	0.18	0.19	0.003	0.040	0.66	1.24
0.60	T	3.18	14.93	14.66	0.21	0.22	0.003	0.039	0.74	2.35
0.70	T	4.75	17.31	17.00	0.27	0.28	0.003	0.039	0.88	4.20
0.80	T	6.57	19.64	19.29	0.33	0.34	0.003	0.038	1.02	6.72
0.90	T	8.59	21.31	20.91	0.40	0.41	0.003	0.038	1.18	10.09
1.00	T	10.74	22.53	22.08	0.48	0.49	0.003	0.037	1.33	14.31
1.10	T	13.00	23.64	23.12	0.55	0.56	0.003	0.037	1.49	19.33
1.20	T	15.38	25.29	24.71	0.61	0.62	0.003	0.036	1.61	24.81
1.30	T	17.89	25.96	25.28	0.69	0.71	0.003	0.036	1.78	31.84
1.40	T	20.43	26.26	25.49	0.78	0.80	0.003	0.035	1.96	40.00
1.50	T	22.99	26.56	25.70	0.87	0.89	0.003	0.035	2.13	49.06
1.60	T	25.57	26.86	25.91	0.95	0.99	0.003	0.034	2.31	59.03
1.70	T	28.17	27.17	26.12	1.04	1.08	0.003	0.034	2.48	69.94
1.80	T	30.80	27.47	26.33	1.12	1.17	0.003	0.033	2.66	81.81
1.90	T	33.44	27.78	26.57	1.20	1.26	0.003	0.033	2.83	94.64
2.00	T	36.11	28.10	26.82	1.28	1.35	0.003	0.032	3.00	108.49
2.10	T	38.80	28.42	27.06	1.37	1.43	0.003	0.032	3.18	123.42
2.20	T	41.52	28.74	27.31	1.44	1.52	0.003	0.031	3.36	139.46
2.30	T	44.27	29.07	27.56	1.52	1.61	0.003	0.031	3.54	156.66
2.40	T	47.04	29.39	27.81	1.60	1.69	0.003	0.030	3.72	175.08

STAGE	ALPHA	FROUDE
0.50	1.00	0.27
0.60	1.00	0.28
0.70	1.00	0.29
0.80	1.00	0.31
0.90	1.00	0.32
1.00	1.00	0.34
1.10	1.00	0.35
1.20	1.00	0.36
1.30	1.00	0.37
1.40	1.00	0.39
1.50	1.00	0.40
1.60	1.00	0.41
1.70	1.00	0.42
1.80	1.00	0.43
1.90	1.00	0.44
2.00	1.00	0.46
2.10	1.00	0.47
2.20	1.00	0.48
2.30	1.00	0.49
2.40	1.00	0.50


c:\programs\wxspro20\wsc.out
29.4
23.5
17.6
11.8
5.9
0.0
PERIM (ft)
0.0
35.0
70.0
105.0
140.1
175.1
Q (cfs)

IN-CLASS PROBLEM #8 - Answer Sheet.
Using RHABSIM to Evaluate Instream Flow Trade-Offs
BLM Training Course No. 7000-12

The Problem:

RHABSIM is a somewhat more user-friendly version of the PHABSIM (Physical Habitat Simulation) model, a key component of the IFIM (Instream Flow Incremental Method). This approach to instream flow determination is likely the most universally applied procedure of its kind and has been used world-wide to develop instream flow recommendations for a myriad of aquatic species. In this exercise, you will apply the output of the RHABSIM model to develop, justify, and defend monthly instream flow recommendations for a small stream having three species of trout. The information provided on the attached pages includes:

1) WUA plots for 3 salmonid species and life stages
2) WUA summary table by species and life stage
3) Mean monthly hydrograph plot
4) Flow duration table

Assignment: (work in pairs)

1) Develop a periodicity chart for each species. (4 charts attached) Bull & brown trout are fall spawners w/ incubation over winter. Cutthroat are spring spawners with fry emergence by summer. See Problem Set #1.

2) Using WUA information, determine optimum flow for each month and life stage for each species. Shown on WUA-Q plots for each species & life stage.

3) Using the 4th periodicity chart, combine the optimum flows for each species, life stage, and month.

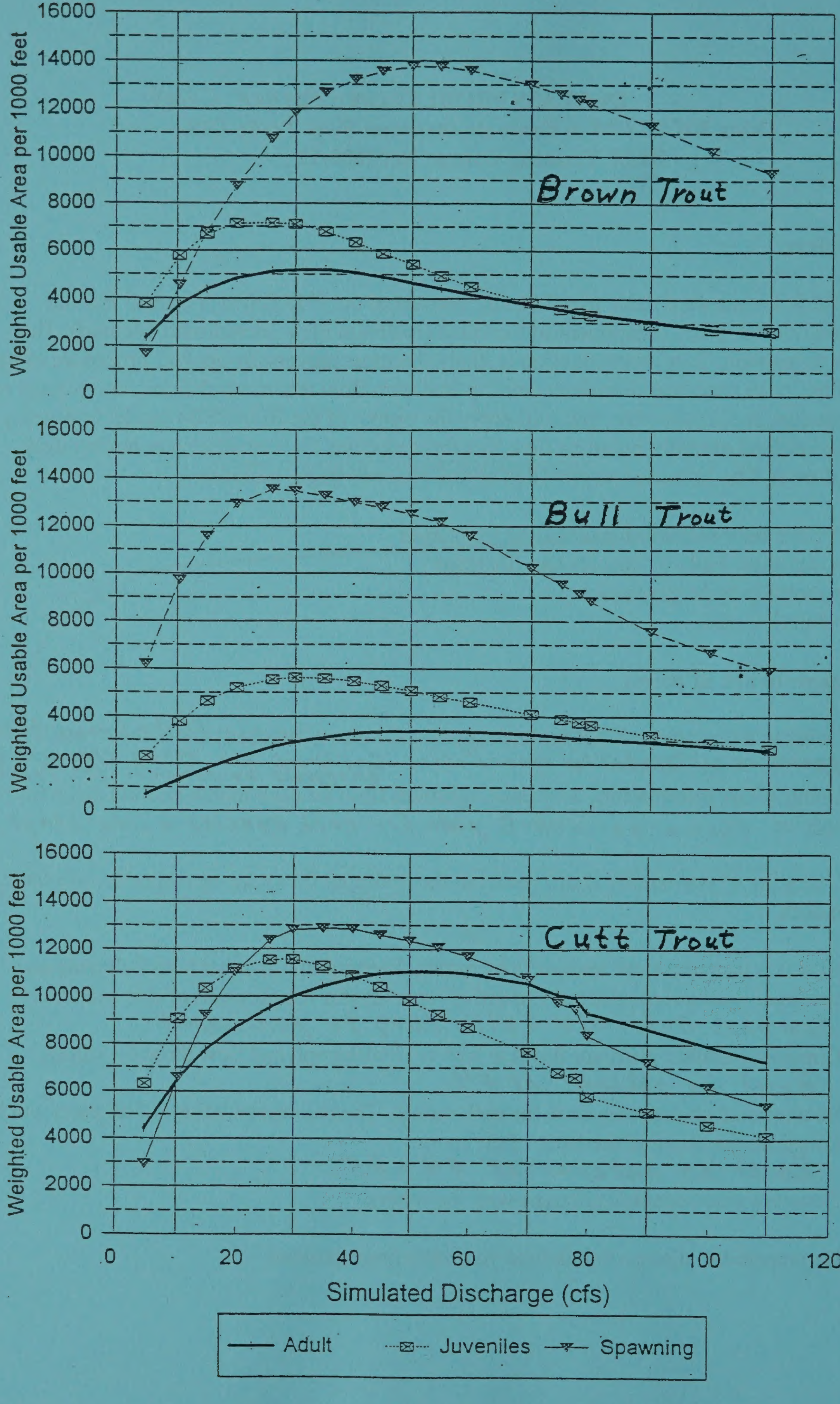
4) Evaluate instream flow trade-offs by month, keeping in mind that both bull trout and cutthroat trout are considered "sensitive" species (for the purposes of this exercise). Somewhat subjective & will vary by participant.

5) Compare monthly instream flows to historic hydrograph and flow duration values. Based on outcome of #4.

6) Recommend an instream flow for each month. The recommendations of all pairs will be tallied on the board at the front of the room. Based on outcome of #4 & #5.

7) Compare your recommendations with the others.

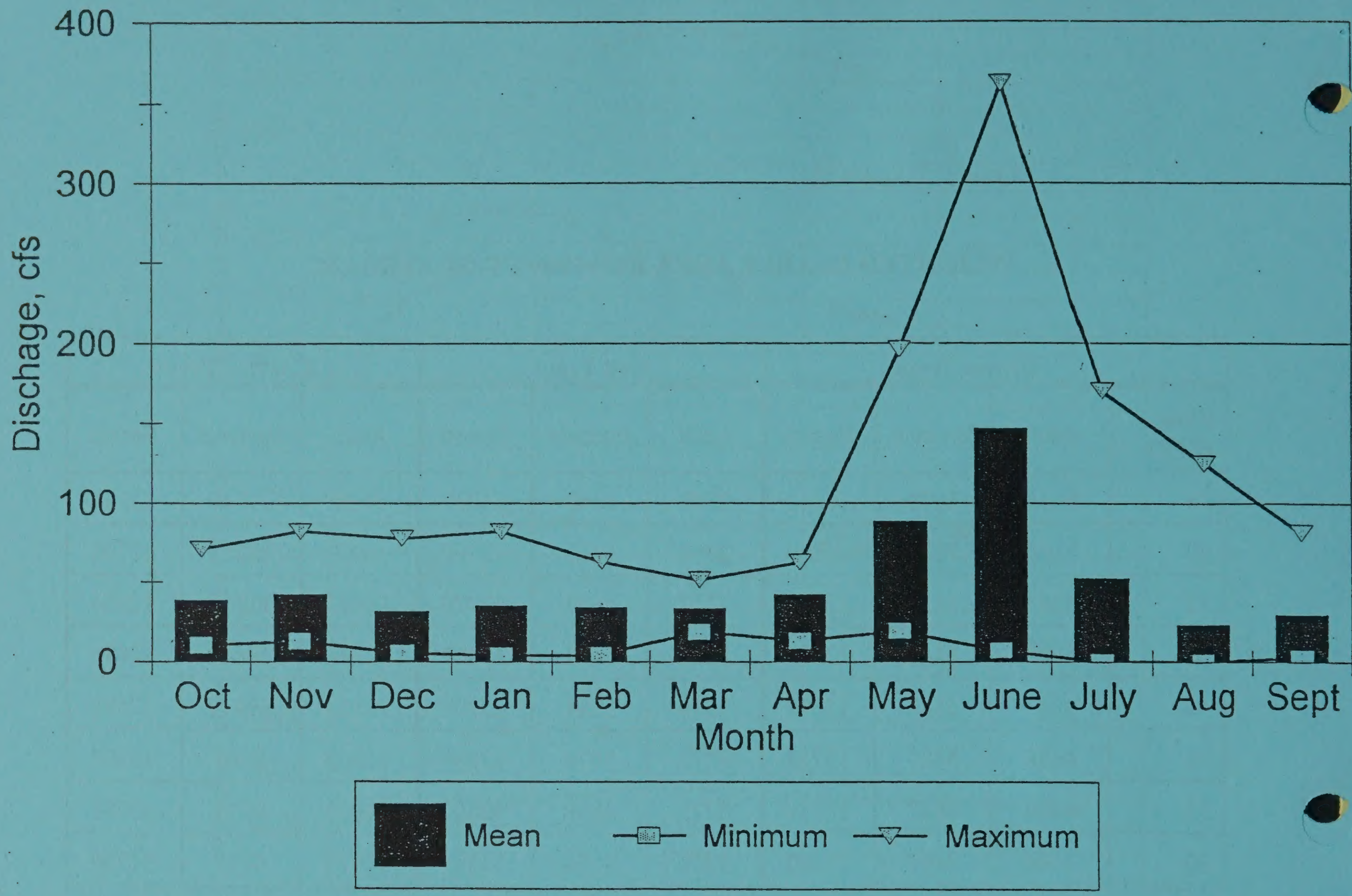
8) Be prepared to discuss and defend your recommendations!



Brown Trout
Bull Trout
Cutt Trout
Weighted Usable Area per 1000 feet
16000
14000
12000
10000
8000
6000
4000
2000
0
0
20
40
60
80
100
120
Simulated Discharge (cfs)
Adult
Juveniles
Spawning

WEIGHTED USABLE AREA PER 1000 FT OF STREAM

	Brown Trout			Bull Trout			Cutt Trout		
Flow (CFS)	Adult	Juvenile	Spawn	Adult	Juvenile	Spawn	Adult	Juvenile	Spawn
26	5115	7178	10742	2703	5549	14033	9528	11549	12364
30	5186	7121	11829	2914	5623	13990	9988	11552	12794
35	5197	6816	12667	3117	5605	13779	10432	11287	12864
40	5080	6347	13214	3268	5463	13462	10746	10888	12836
45	4889	5887	13575	3356	5294	13208	10951	10417	12597
50	4638	5420	13762	3372	5078	12889	11060	9841	12337
55	4400	4937	13749	3375	4839	12507	11062	9271	12081
60	4166	4492	13592	3358	4594	11899	10974	8719	11709



% Time Flow Equaled or Exceeded				
Flow (cfs)	**Oct-Dec**	**Jan-March**	**April-June**	**July-Sept**
20	76	79	89	43
30	63	55	78	33
40	46	42	70	29
50	33	25	60	26
60	25	12	51	23

PERIODICITY CHART

Species: Cutthroat Trout

System: Southwest River

Microhabitat	MONTH											
Usage	J	F	M	A	M	J	J	A	S	O	N	D
Adults												
Summer resting												
Winter Resting												
Spawning												
Incubation												
Fry/Larvae												
Juvenile												
Feeding												
Aquatic source												
Adult												
Juvenile												
Fry												
Terrestrial source												
Adult												
Juvenile												
Fry												

PERIODICITY CHART

Species: Trout

System: Southwest River

Microhabitat

MONTH

Usage	J	F	M	A	M	J	J	A	S	O	N	D
Adults												
Summer resting												
Winter Resting												
Spawning												
Incubation												
Fry/Larvae												
Juvenile												
Feeding												
Aquatic source												
Adult												
Juvenile												
Fry												
Terrestrial source												
Adult												
Juvenile												
Fry												

PERIODICITY CHART

Species: Trout		System: Southwest River
Microhabitat		MONTH
Usage		J F M A M J J A S O N D

Adults
- Summer resting
- Winter Resting
- Spawning
- Incubation

Fry/Larvae

Juvenile

Feeding
- Aquatic source
  - Adult
  - Juvenile
  - Fry
- Terrestrial source
  - Adult
  - Juvenile
  - Fry

PERIODICITY CHART

Species: Trout   System: Southwest River

Microhabitat   MONTH

Usage   J F M A M J J A S O N D

Adults

Summer resting

Winter Resting

Spawning

Incubation

Fry/Larvae

Juvenile

Feeding

Aquatic source

Adult

Juvenile

Fry

Terrestrial source

Adult

Juvenile

Fry

IN-CLASS PROBLEM #9 - Answer Sheet.
Barrier Analysis for Cutthroat Trout
BLM Training Course No. 7000-12

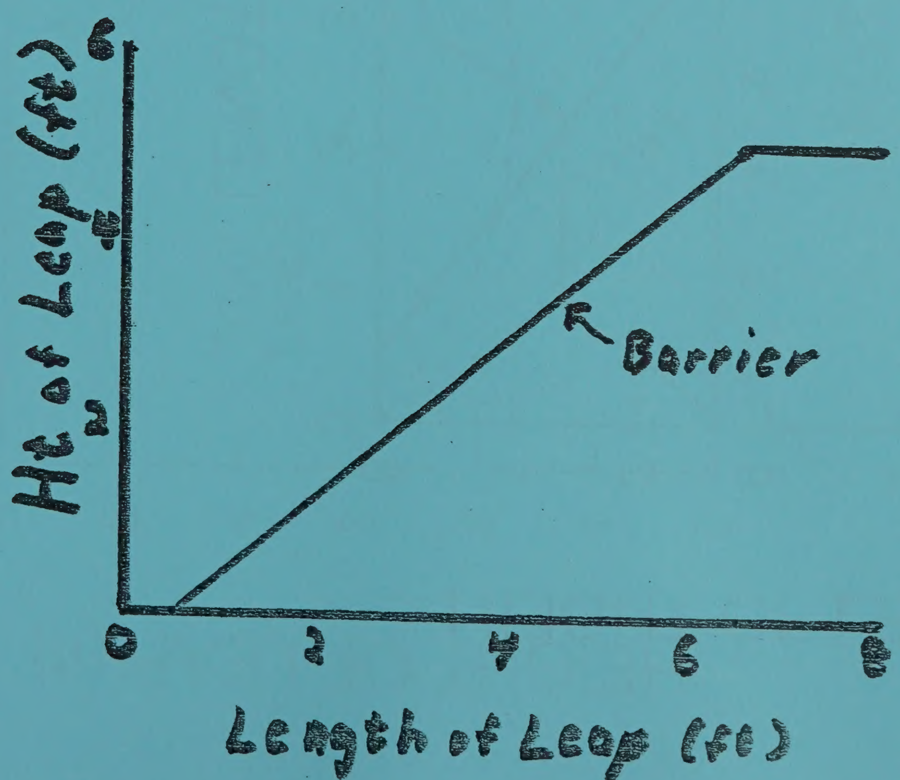
The Problem:

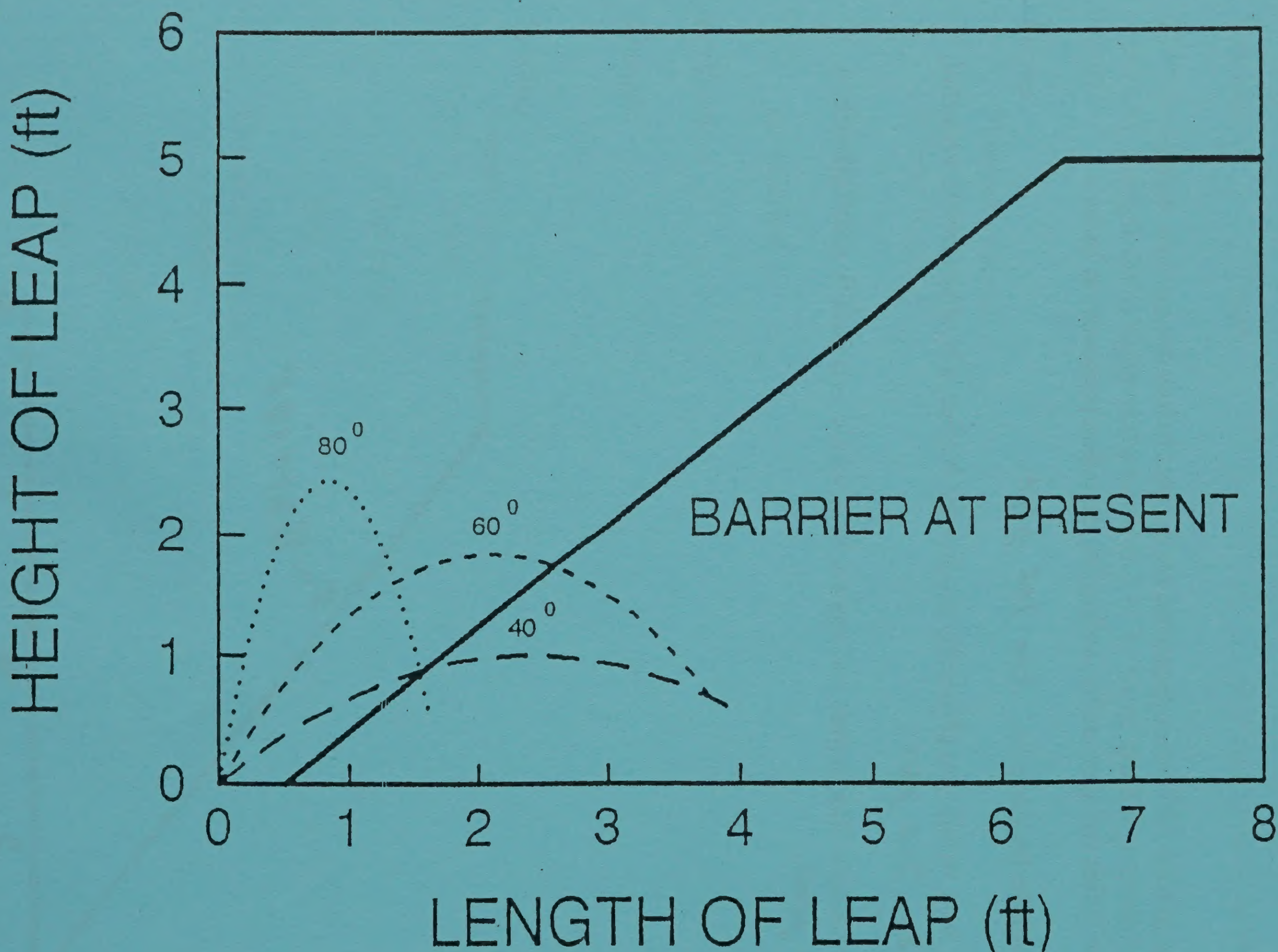
Are cutthroat trout able to pass the barrier presented on the plot below during their spring spawning migration? Assuming a burst speed of 13.0 ft/s and a leap angle of 60 degrees, analyze the barrier to determine if fish can pass using the leaping equation presented in lecture.

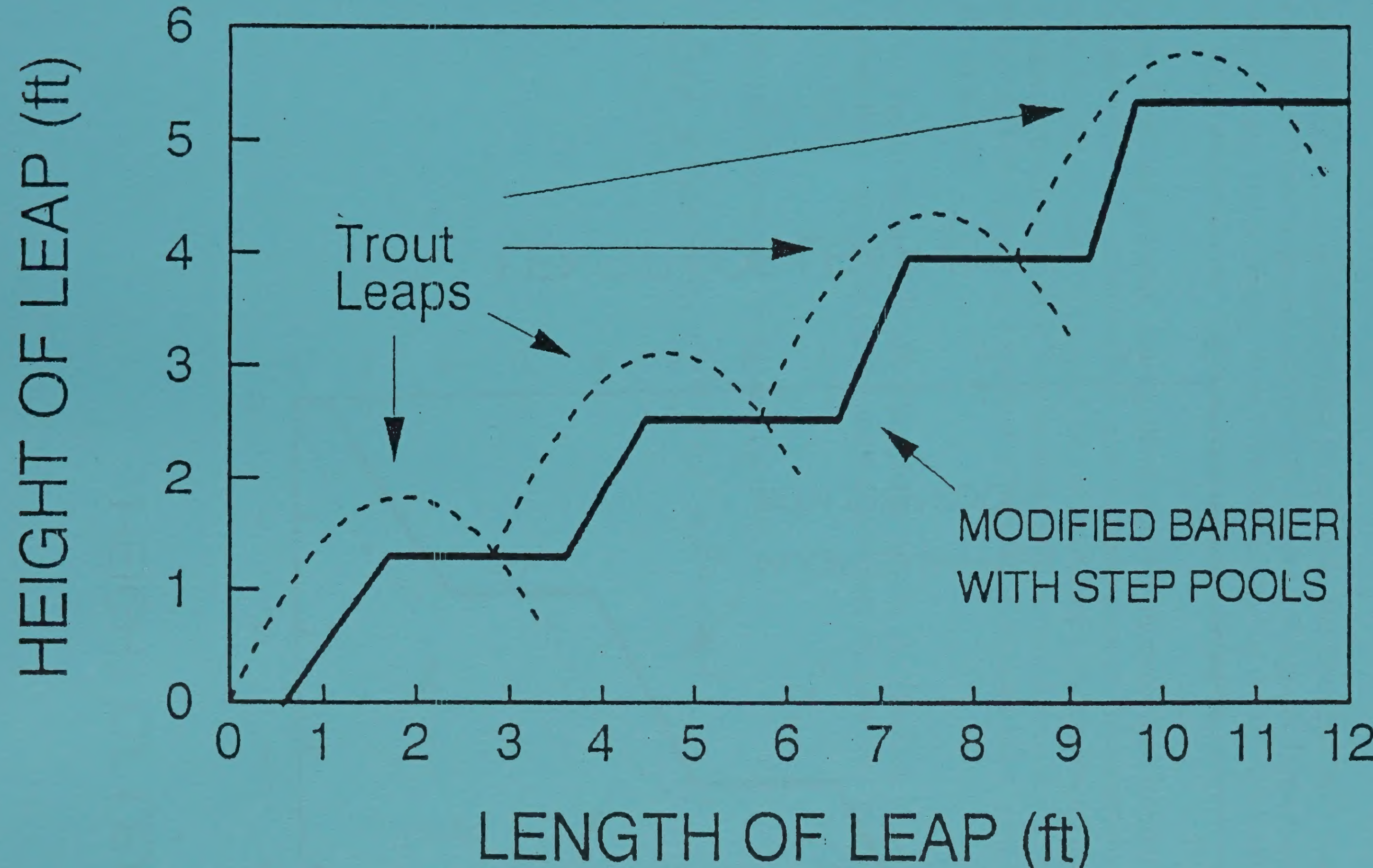
Plot the leaping curve on the barrier plot. See 1st plot.

If the fish cannot pass, how would you physically modify the barrier, a boulder/cobble waterfall, to assure passage? See 2nd plot.

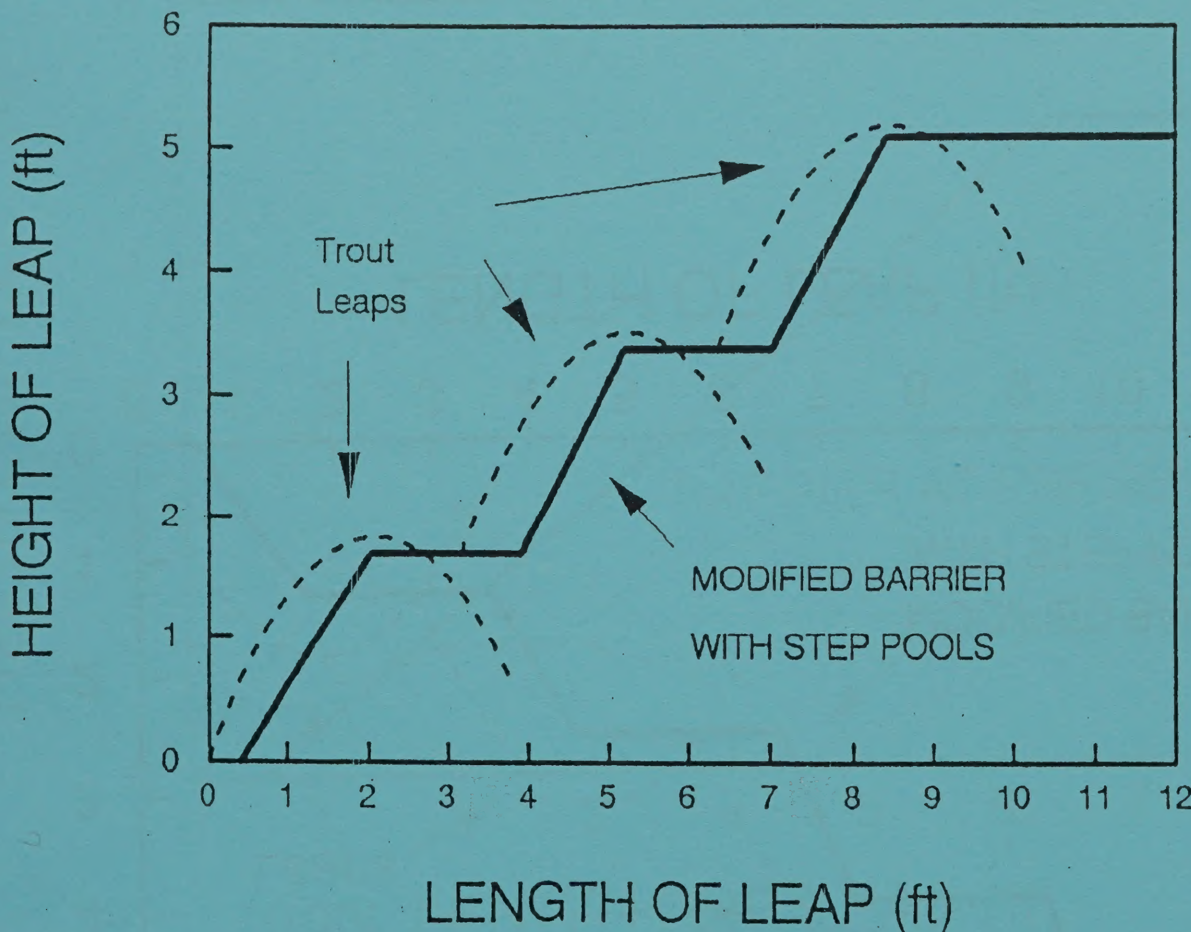
If you wanted only the hardiest fish to pass and spawn, how would you modify your restoration plan? See 3rd plot.




HEIGHT OF LEAP (ft)
6
5
4
3
2
1
0
80°
60°
40°
BARRIER AT PRESENT
0
1
2
3
4
5
6
7
8
LENGTH OF LEAP (ft)



HEIGHT OF LEAP (ft)
6
5
4
3
2
1
0
0
1
2
3
4
5
6
7
8
9
10
11
12
LENGTH OF LEAP (ft)
Trout Leaps
MODIFIED BARRIER WITH STEP POOLS



HEIGHT OF LEAP (ft)
6
5
4
3
2
1
0
Trout
Leaps
MODIFIED BARRIER
WITH STEP POOLS
0
1
2
3
4
5
6
7
8
9
10
11
12
LENGTH OF LEAP (ft)

IN-CLASS PROBLEM #10 - Answer Sheet
Douglas Creek Culvert Analysis & Design
BLM Training Course 7000-12

The Problem:

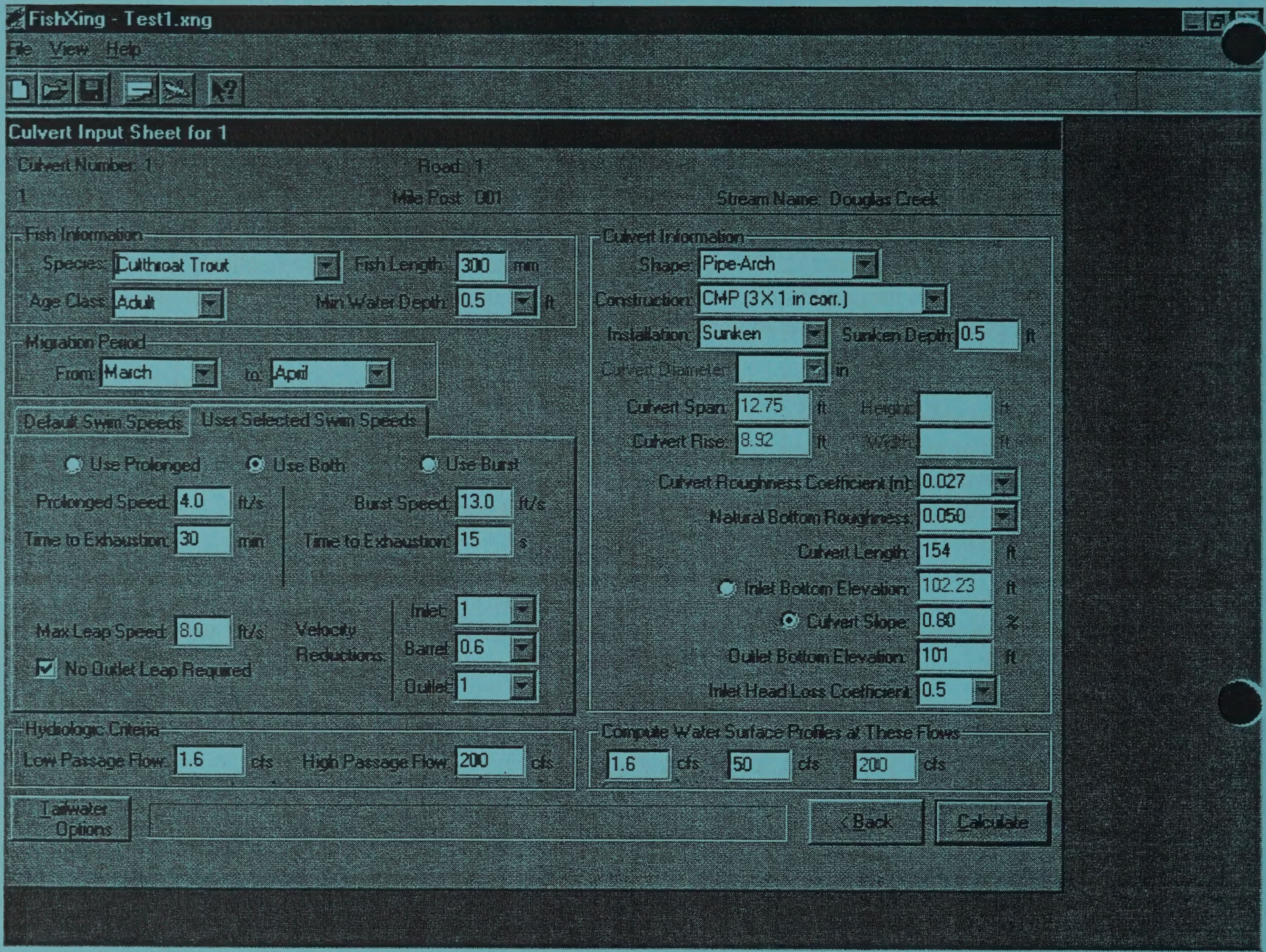
Engineers are planning to install a new culvert under the Douglas Creek road. The present design calls for a 154 ft steel pipe arch (12'10" x 8"4") on a 0.8% grade. Hydrologic studies indicate the culvert will carry flows ranging from 1.6 to 200 cfs during the spring runoff season, the same time during which cutthroat trout will be moving upstream to spawn.

Using the FishXing software, analyze the design the engineers are planning to use to determine if cutthroats will be able to successfully pass upstream through the culvert on their spawning run. Assume no inlet or outlet problems exist and a constant tailwater condition with 101.5 ft as the pool surface elevation and 99.0 ft as the outlet pool bottom elevation. Use the User selected swim speeds, with a prolonged speed of 4.0 ft/s for 30 minutes and a burst speed of 13.0 ft/s for 15 seconds.

If the fish cannot successfully pass through the culvert, use FishXing to re-design the culvert so that design flows can still be carried and the cutthroats can pass. The length of the culvert must remain at 154 ft.

Compare and discuss your results with the class.

One possible solution attached.


FishXing - Test1.xng
File View Help
Culvert Input Sheet for 1
Culvert Number: 1
Road: 1
Mile Post: 001
Stream Name: Douglas Creek
Fish Information
Species: Cutthroat Trout
Fish Length: 300 mm
Age Class: Adult
Min Water Depth: 0.5 ft
Migration Period
From: March to: April
Default Swim Speeds
User Selected Swim Speeds
Use Prolonged
Use Both
Use Burst
Prolonged Speed: 4.0 ft/s
Time to Exhaustion: 30 min
Burst Speed: 13.0 ft/s
Time to Exhaustion: 15 s
Max Leap Speed: 8.0 ft/s
No Outlet Leap Required
Velocity Reductions
Inlet: 1
Barrel: 0.6
Outlet: 1
Culvert Information
Shape: Pipe-Arch
Construction: CMP (3 X 1 in corr.)
Installation: Sunken
Sunken Depth: 0.5 ft
Culvert Diameter: in
Culvert Span: 12.75 ft
Height: ft
Culvert Rise: 8.92 ft
Width: ft
Culvert Roughness Coefficient (n): 0.027
Natural Bottom Roughness: 0.050
Culvert Length: 154 ft
Inlet Bottom Elevation: 102.23 ft
Culvert Slope: 0.80 %
Outlet Bottom Elevation: 101 ft
Inlet Head Loss Coefficient: 0.5
Hydrologic Criteria
Low Passage Flow: 1.6 cfs
High Passage Flow: 200 cfs
Compute Water Surface Profiles at These Flows
1.6 cfs
50 cfs
200 cfs
Tailwater Options
< Back
Calculate

Culvert Report for 1

Culvert Installation Data

Culvert Type: 157 X 101 in Pipe-Arch
Construction: CMP (3 X 1 in corr.)
Installation: Sunken
Countersunk Depth: 0.5 ft
Culvert Length: 154 ft
Culvert Slope: 0.80%
Culvert Roughness Coefficient: 0.027
Natural Bottom Roughness Coefficient: 0.05
Inlet Invert Elevation: 102.23 ft
Outlet Invert Elevation: 101 ft
Inlet Headloss Coefficient (Ke): 0.5

Design Flows

Low Passage Flow: 1.6 cfs
High Passage Flow: 200 cfs

Embedded Culverts

Embedded culverts, also commonly known as sunken, countersunk, or depressed culverts, have their bottom placed below the streambed. This placement results in a culvert with natural substrate along the bottom, typically increasing the bed roughness and resulting in lower velocities.

The sunken culvert option can also be used to model metal pipes with concrete-lined bottoms. Choose **Sunken** and enter the approximate depth and roughness of the concrete.

Table 1. Uniform Flow Calculations.

Discharge (cfs)	Velocity (ft/s)	Normal Depth (ft)	Critical Depth (ft)	Outlet Velocity (ft/s)	Tailwater Depth (ft)	Pool Depth (ft)	Min Rqd. Leap Velocity (ft/s)	Vert. Leap Distance (ft)	Comments
0.00	0.00	0.00	0.00	0.00	0.50	2.50			
0.47	0.58	0.10	0.05	0.10	0.50	2.50	0.00	0.00	Depth
1.58	0.94	0.20	0.11	0.35	0.50	2.50	0.00	0.00	Depth
1.60	0.94	0.20	0.11	0.35	0.50	2.50	0.00	0.00	LPF; Depth
3.23	1.23	0.30	0.17	0.71	0.50	2.50	0.00	0.00	Depth
5.39	1.50	0.40	0.24	1.18	0.50	2.50	0.00	0.00	Depth
8.02	1.75	0.50	0.30	1.75	0.50	2.50	0.00	0.00	
11.13	1.99	0.60	0.38	2.43	0.50	2.50	0.00	0.00	
14.69	2.21	0.70	0.45	3.21	0.50	2.50	0.00	0.00	
18.69	2.42	0.80	0.52	3.90	0.50	2.50	0.00	0.00	
23.13	2.63	0.90	0.60	4.16	0.50	2.50	0.00	0.00	
27.99	2.82	1.00	0.67	4.41	0.50	2.50	0.00	0.00	
33.26	3.01	1.10	0.75	4.64	0.50	2.50	0.00	0.00	
38.94	3.20	1.20	0.83	4.87	0.50	2.50	0.00	0.00	
45.02	3.38	1.30	0.90	5.09	0.50	2.50	0.00	0.00	
51.49	3.55	1.40	0.98	5.30	0.50	2.50	0.00	0.00	
58.33	3.72	1.50	1.06	5.50	0.50	2.50	0.00	0.00	
65.54	3.88	1.60	1.14	5.70	0.50	2.50	0.00	0.00	
73.11	4.04	1.70	1.22	5.89	0.50	2.50	0.00	0.00	Vel
81.03	4.20	1.80	1.30	6.07	0.50	2.50	0.00	0.00	Vel
89.29	4.35	1.90	1.38	6.25	0.50	2.50	0.00	0.00	Vel
97.88	4.50	2.00	1.46	6.43	0.50	2.50	0.00	0.00	Vel
106.79	4.64	2.10	1.54	6.60	0.50	2.50	0.00	0.00	Vel
116.01	4.78	2.20	1.62	6.77	0.50	2.50	0.00	0.00	Vel
125.53	4.92	2.30	1.70	6.94	0.50	2.50	0.00	0.00	Vel
135.33	5.06	2.40	1.78	7.10	0.50	2.50	0.00	0.00	Vel
145.42	5.19	2.50	1.86	7.26	0.50	2.50	0.00	0.00	Vel
155.77	5.32	2.60	1.94	7.41	0.50	2.50	0.00	0.00	Vel
166.37	5.44	2.70	2.02	7.56	0.50	2.50	0.00	0.00	Vel
177.21	5.57	2.80	2.10	7.71	0.50	2.50	0.00	0.00	Vel
188.29	5.69	2.90	2.18	7.86	0.50	2.50	0.00	0.00	Vel
199.58	5.80	3.00	2.25	8.00	0.50	2.50	0.00	0.00	Vel
200.00	5.81	3.00	2.26	8.01	0.50	2.50	0.00	0.00	HPF; Vel
211.08	5.92	3.10	2.33	8.15	0.50	2.50	0.00	0.00	Vel
222.77	6.03	3.20	2.41	8.29	0.50	2.50	0.00	0.00	Vel
234.64	6.14	3.30	2.49	8.42	0.50	2.50	0.00	0.00	Vel
246.67	6.25	3.40	2.56	8.56	0.50	2.50	0.00	0.00	Vel
258.85	6.35	3.50	2.64	8.69	0.50	2.50	0.00	0.00	Vel
271.17	6.45	3.60	2.71	8.82	0.50	2.50	0.00	0.00	Vel
283.60	6.55	3.70	2.79	8.95	0.50	2.50	0.00	0.00	Vel
296.14	6.65	3.80	2.86	9.08	0.50	2.50	0.00	0.00	Vel
308.77	6.74	3.90	2.93	9.21	0.50	2.50	0.00	0.00	Vel
321.47	6.83	4.00	3.01	9.33	0.50	2.50	0.00	0.00	Vel
334.21	6.92	4.10	3.08	9.45	0.50	2.50	0.00	0.00	Vel
347.00	7.01	4.20	3.15	9.57	0.50	2.50	0.00	0.00	Vel

Comment Codes:

LPF - Low Passage Flow

Table 2. Gradually Varied Flow Calculations for 1.6 cfs.

Q = 1.6 cfs				
Dist Down Culvert (ft)	Depth (ft)	Velocity (ft/s)	Curve	Swim Mode
0	0.22	0.00	Inlet	
3	0.20	1.15	Normal	Prolonged
9	0.20	0.94	Normal	Prolonged
17	0.20	0.94	Normal	Prolonged
25	0.20	0.94	Normal	Prolonged
33	0.20	0.94	Normal	Prolonged
41	0.20	0.94	Normal	Prolonged
49	0.20	0.94	Normal	Prolonged
57	0.20	0.94	Normal	Prolonged
65	0.20	0.94	Normal	Prolonged
73	0.20	0.94	Normal	Prolonged
81	0.20	0.94	Normal	Prolonged
89	0.20	0.94	Normal	Prolonged
97	0.20	0.94	Normal	Prolonged
105	0.21	0.89	M1	Prolonged
113	0.23	0.81	M1	Prolonged
121	0.27	0.69	M1	Prolonged
129	0.32	0.58	M1	Prolonged
137	0.37	0.48	M1	Prolonged
145	0.43	0.41	M1	Prolonged
154	0.50	0.35	M1	Prolonged

Table 3. Gradually Varied Flow Specifications for 1.6 cfs.

	1.6 cfs
Normal Depth (ft)	0.20
Critical Depth (ft)	0.11
Headwater Depth (ft)	0.22
Inlet Velocity (ft/s)	1.15
Tailwater Depth (ft)	0.50
Burst Swim Time (s)	0.00
Prolonged Swim Time (min	0.74
Barrier Code	Depth

Barrier Codes

Depth - Too shallow for substantial distance

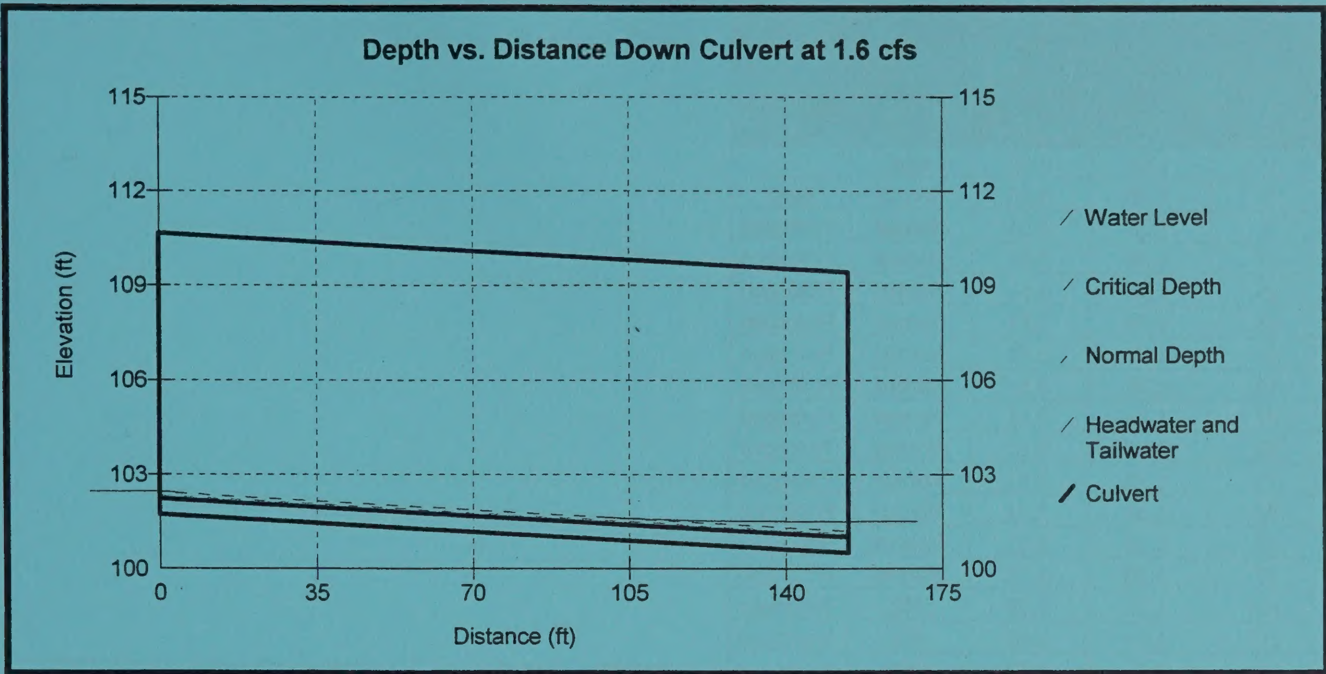


Figure 3. Water Surface Profile at 1.6 cfs

Table 4. Gradually Varied Flow Calculations for 50 cfs.

Q = 50.0 cfs				
Dist Down Culvert (ft)	Depth (ft)	Velocity (ft/s)	Curve	Swim Mode
0	1.66	0.00	Inlet	
3	1.38	4.30	Normal	Burst
9	1.38	3.51	Normal	Prolonged
17	1.38	3.51	Normal	Prolonged
25	1.38	3.51	Normal	Prolonged
33	1.38	3.51	Normal	Prolonged
41	1.38	3.51	Normal	Prolonged
49	1.38	3.51	Normal	Prolonged
57	1.38	3.51	Normal	Prolonged
65	1.38	3.51	Normal	Prolonged
73	1.38	3.51	Normal	Prolonged
81	1.38	3.51	Normal	Prolonged
89	1.38	3.51	Normal	Prolonged
97	1.38	3.51	Normal	Prolonged
105	1.35	3.59	M2	Prolonged
113	1.34	3.62	M2	Prolonged
121	1.32	3.67	M2	Prolonged
129	1.31	3.73	M2	Prolonged
137	1.28	3.83	M2	Prolonged
145	1.23	3.99	M2	Prolonged
150.1	1.15	4.29	M2	Prolonged
154	0.71	7.39	Outfall	Prolonged

Table 5. Gradually Varied Flow Specifications for 50 cfs.

	50.0 cfs
Normal Depth (ft)	1.38
Critical Depth (ft)	0.97
Headwater Depth (ft)	1.66
Inlet Velocity (ft/s)	4.30
Tailwater Depth (ft)	0.50
Burst Swim Time (s)	0.34
Prolonged Swim Time (min	1.46
Barrier Code	NONE

Barrier Codes

NONE - No Barrier

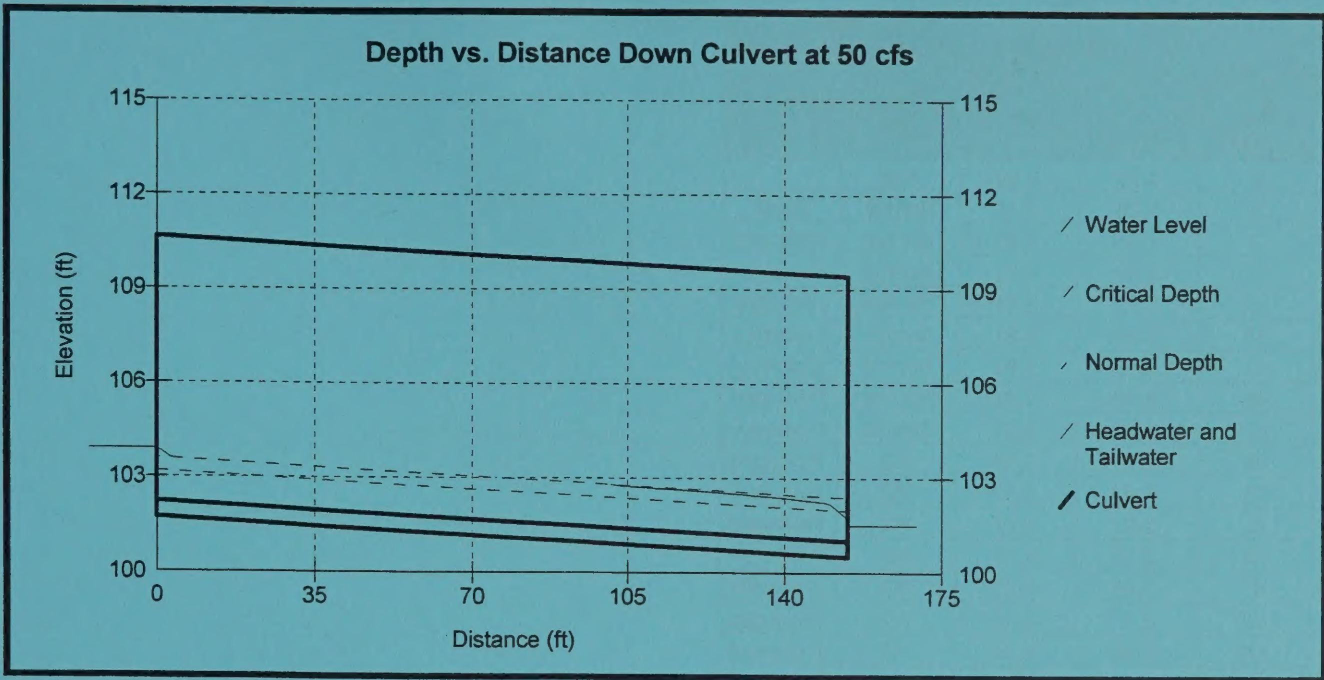


Figure 4. Water Surface Profile at 50 cfs

Table 6. Gradually Varied Flow Calculations for 200 cfs.

Q = 200.0 cfs				
Dist Down Culvert (ft)	Depth (ft)	Velocity (ft/s)	Curve	Swim Mode
0	3.79	0.00	Inlet	
3	3.00	7.11	Normal	Burst
9	3.00	5.81	Normal	Prolonged
17	3.00	5.81	Normal	Prolonged
25	3.00	5.81	Normal	Prolonged
33	3.00	5.81	Normal	Prolonged
41	3.00	5.81	Normal	Prolonged
49	3.00	5.81	Normal	Prolonged
57	3.00	5.81	Normal	Prolonged
65	2.94	5.96	M2	Prolonged
73	2.92	5.98	M2	Prolonged
81	2.91	6.01	M2	Prolonged
89	2.90	6.04	M2	Prolonged
97	2.89	6.07	M2	Prolonged
105	2.87	6.12	M2	Prolonged
113	2.84	6.18	M2	Prolonged
121	2.82	6.24	M2	Prolonged
129	2.79	6.32	M2	Prolonged
137	2.74	6.43	M2	Prolonged
145.0	2.61	6.79	M2	Burst
154	1.67	11.28	Outfall	Burst

Table 7. Gradually Varied Flow Specifications for 200 cfs.

	200.0 cfs
Normal Depth (ft)	3.00
Critical Depth (ft)	2.26
Headwater Depth (ft)	3.79
Inlet Velocity (ft/s)	7.11
Tailwater Depth (ft)	0.50
Burst Swim Time (s)	1.92
Prolonged Swim Time (min	7.19
Barrier Code	NONE

Barrier Codes

NONE - No Barrier

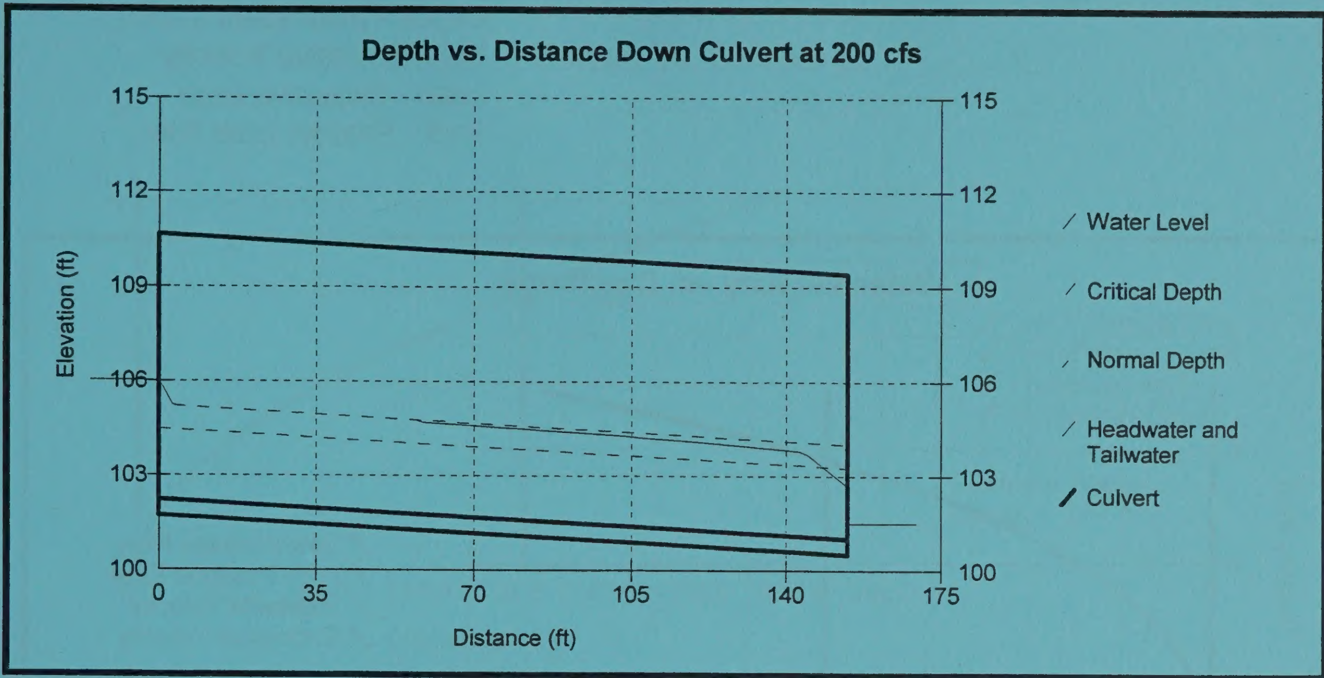


Figure 5. Water Surface Profile at 200 cfs

<u>Tailwater Information</u>

Constant Tailwater Elevation: 101.5 ft

Outlet-Pool Bottom Elevation: 99 ft

HPF - High Passage Flow
Depth - Insufficient Depth
Vel - Excessive Velocity
Leap - Excessive Leap
Pool - Shallow Leap Pool

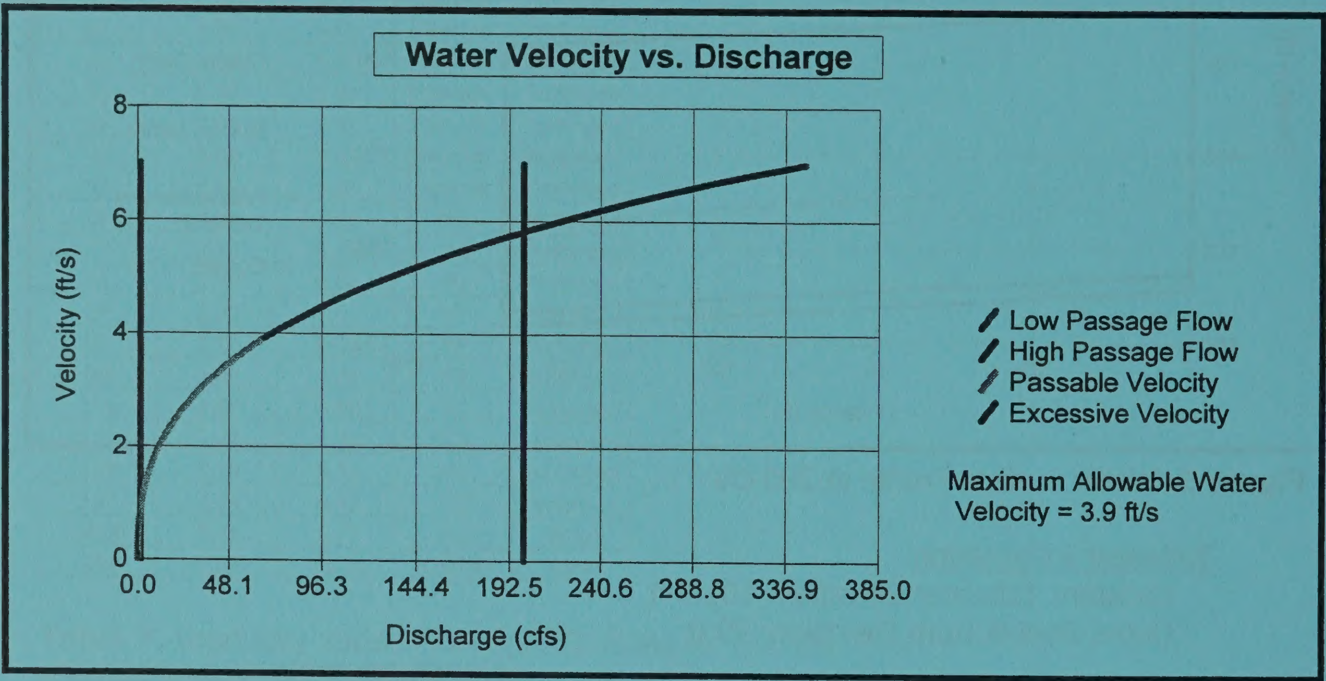


Figure 1. Velocity at Uniform Flow

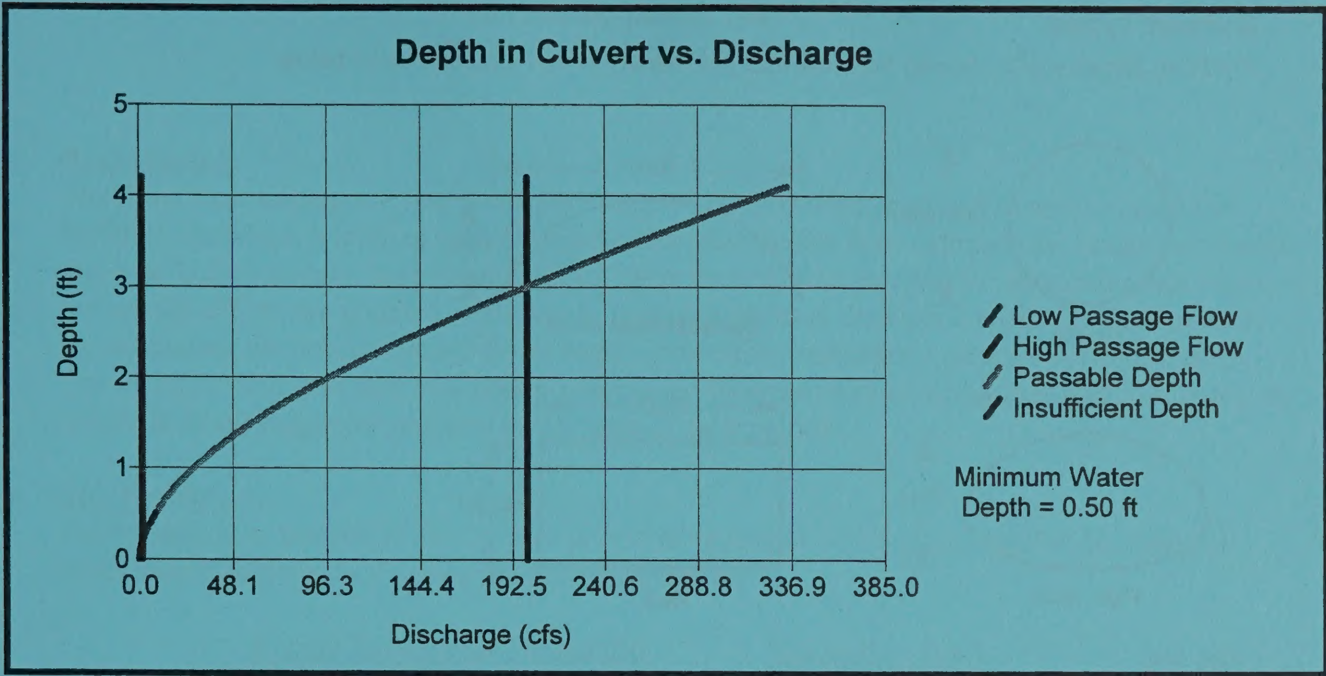
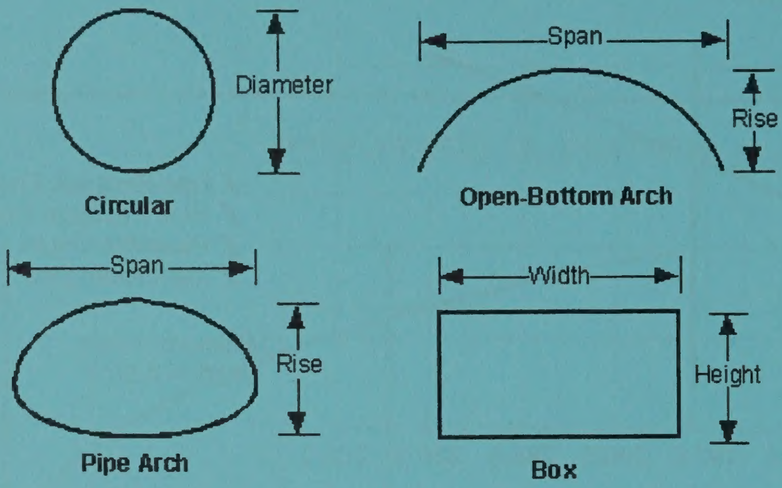


Figure 2. Depth at Uniform Flow

Culvert Types

FishXing allows you to choose from the four predefined culvert shapes shown below.



Also see:
Construction Materials

IN-CLASS PROBLEM #11 – Answer Sheet
Determining Design Flow
BLM Training Course 7000-12

Background:

The flood flow having a 2 year recurrence interval (Q_{F2}) is often assumed to approximate the bankfull discharge, a level commonly used as the high design flow estimate for stream restoration projects. Unfortunately, long-term U.S.G.S. gage records seldom exist for stream reaches where restoration efforts are planned. As a result, hydrologists have developed easily applied methods for estimating the needed design flows based upon either watershed or channel characteristics. This exercise will give you experience in applying these estimation techniques and comparing the results to flood frequency analysis of 25 years of gage records.

The Problem:

Flood frequency analysis of the 25 year period-of-record at USGS gage #06274500, Greybull River near Pitchfork, WY yields the following results:

Annual Exceedance Probability	Streamflow (cfs)
0.99	720
0.95	952
0.90	1116
0.80	1367
0.50	2081
0.20	3305
0.10	4283
0.04	5724

Based upon this analysis, what is the Q_{F2} ? 2081 cfs

Based upon Lowham's (1988) watershed characteristics model for Wyoming mountain streams, $Q_{F2} = 0.012A^{0.88}(ELEV/1000)^{3.25}$, where A is watershed area (260 sq miles) and ELEV is mean basin elevation (9000 ft), what is the estimated Q_{F2} ? 2020 cfs

Based upon Lowham's (1988) channel characteristics model for Wyoming mountain streams, $Q_{F2} = 1.94W^{1.58}$, where W is active channel width (95 ft) measured just downstream from a meander, what is the estimated Q_{F2} ? 2586 cfs

Compare your two estimates to the value based upon the gage record.

Which estimate is furthest from the gaged value? Why might this be?

Channel width model estimate is furthest. The channel has probably widened out due to its sandy composition and intensive land uses such as grazing.

IN-CLASS PROBLEM #12 - Answer Sheet
Boulder Stability
BLM Training Course 7000-12

The Problem:

You are designing a boulder placement as part of a structural habitat management program for a mountain stream. At your high design flow, water depth will be 3.0 ft at your anticipated boulder site. Channel slope is 4.0%, or 0.04. You prefer to use 2.0 ft diameter boulders since they are available close to the site.

Using the Shield's relation, Lane's relation, and the Highway Research Board relationship, as presented in the Power Point presentation, evaluate the stability of a 2.0 ft diameter boulder at your high design flow. Assume R = D; specific weight of water = 62.4lbs/ft^3; specific weight of the boulder = 165lbs/ft^3; and k = 0.03.

Shear stress acting on channel boundary = 7.5 lbs/ft^2. $\tau_o = \gamma_w DS = (62.4)(3.0)(.04)$

Critical shear using Shield's relation = 6.2 lbs/ft^2. Will boulder move? Yes
$\tau_c = k(\gamma_s - \gamma_w)d = .03(165-62.4)2.0$

Critical shear using Lane's relation = 10.0 lbs/ft^2. Will boulder move? No
$\tau_c = 0.0164\, d_{75(mm)} = .0164(610)$

Critical shear using HRB relation = 8.0 lbs/ft^2. Will boulder move? No
$\tau_c = 4(2.0)$

If results are mixed, what should you do?

1) Use larger rock
2) Use rock clusters
3) Anchor into bed

IN-CLASS PROBLEM #13 Answer Sheet.
Applying Stream Reach Inventory & Channel Stability Evaluation
Santa Fe River below Santa Fe, NM
BLM Training Course 7000-12

The Problem:

1. Review the Power Point photographs of the Santa Fe River.

2. Using the attached field form and the manual (handout), rate the 15 parameters.

3. Tally score and determine condition class.

4. Discuss applicability of SRI/CSE to the streams you work on. Is it a usable tool? How might you alter the parameters to better meet your needs?

Ratings + answers are subjective + may vary considerably among participants. Scores will likely range from ~90 (Fair) to ~120 (Poor).

IN-CLASS PROBLEM #14 – Answer Sheet
Evaluating Log Overpour Hydraulics
BLM Training Course 7000-12

The Problem:

A low flow notch is often cut into a log overpour structure to concentrate the low flow into the downstream plunge pool and to keep the entire log continually wetted to prevent rot. You are designing a log overpour for a small stream that is 10 ft wide and has a bankfull depth of 3.0 ft. Your design low flow is 2.0 cfs and design high flow is 50 cfs. The elevation of the top of your log overpour (excluding the low flow notch) will be 1.5 ft above the streambed. See the diagram below.

Using the weir flow equation, solve the following:

$Q = cLH^{3/2}$, where
- Q = flow (cfs)
- c = 2.5, a head loss coefficient for log weirs
- L = weir length (ft)
- H = depth, or head, over the weir (ft)

1) If the desired width of your low flow notch is 2.0 ft, how deep should the notch be to just pass your design low flow?

$$H^{3/2} = \frac{Q}{cL} = \frac{2.0}{2.5(2.0)} = 0.4$$

$$H = 0.4^{2/3} = \underline{0.54'} = \text{Notch depth}$$

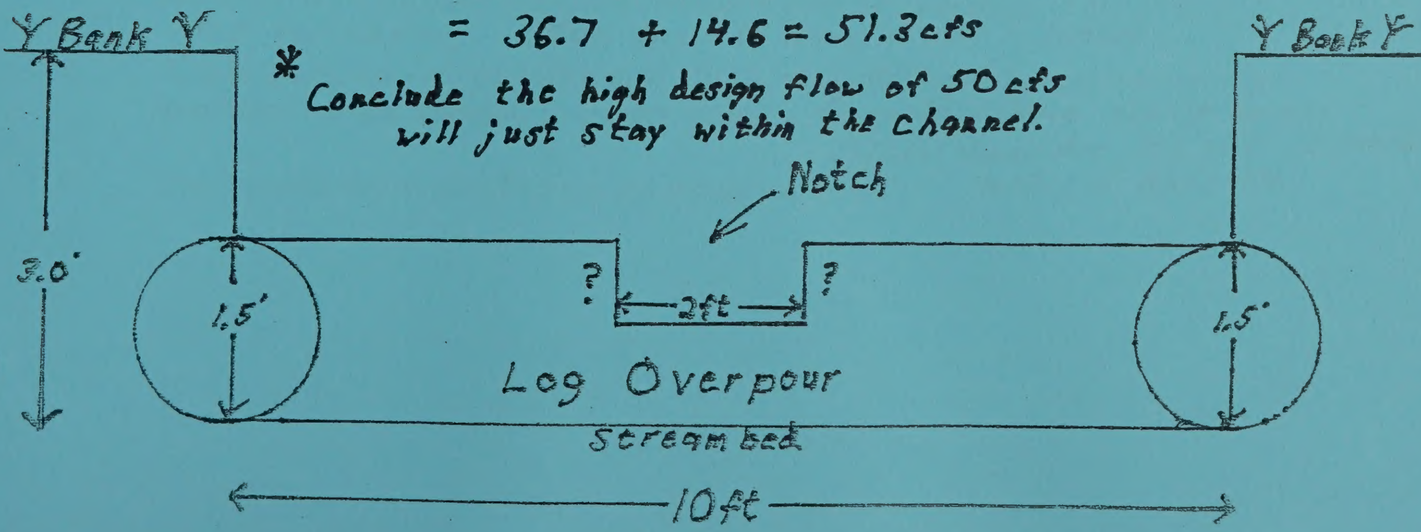
2) Taking into consideration the depth of the low flow notch determined in Question 1, will your high design flow of 50 cfs be able to pass the log overpour structure without spilling over the top of the stream banks?

At bankfull, H over 8' of log = 1.5'
" " " H over 2' of log = 1.5' + 0.54' = 2.04'

So, $Q = [2.5(8)1.5^{3/2}] + [2.5(2)\,2.04^{3/2}]$

$= 36.7 + 14.6 = 51.3$ cfs

* Conclude the high design flow of 50 cfs will just stay within the channel.



IN-CLASS PROBLEM #15 – Answer Sheet
Using WinXSPRO to Evaluate Restoration Options
BLM Training Course No. 7000-12

The Problem:

WinXSPRO is a user-friendly computer program that can be applied to the solution of many aquatic habitat restoration questions. Based upon data from a single cross-section, both hydraulic and sediment transport predictions can be made to evaluate restoration options over a range of flow conditions. Earlier in Problem #7, we used the program to develop instream flow recommendations. In this exercise, we will apply the bedload transport options within WinXSPRO to assess the feasibility of spawning gravel placements.

Your assignment is as follows:

1. Load the WinXSPRO program and review the bedload transport options.

2. We will use the same cross-section data for this exercise as we did for Problem #7, and assume the D_{50} of the substrate is 50mm (coarse gravel).

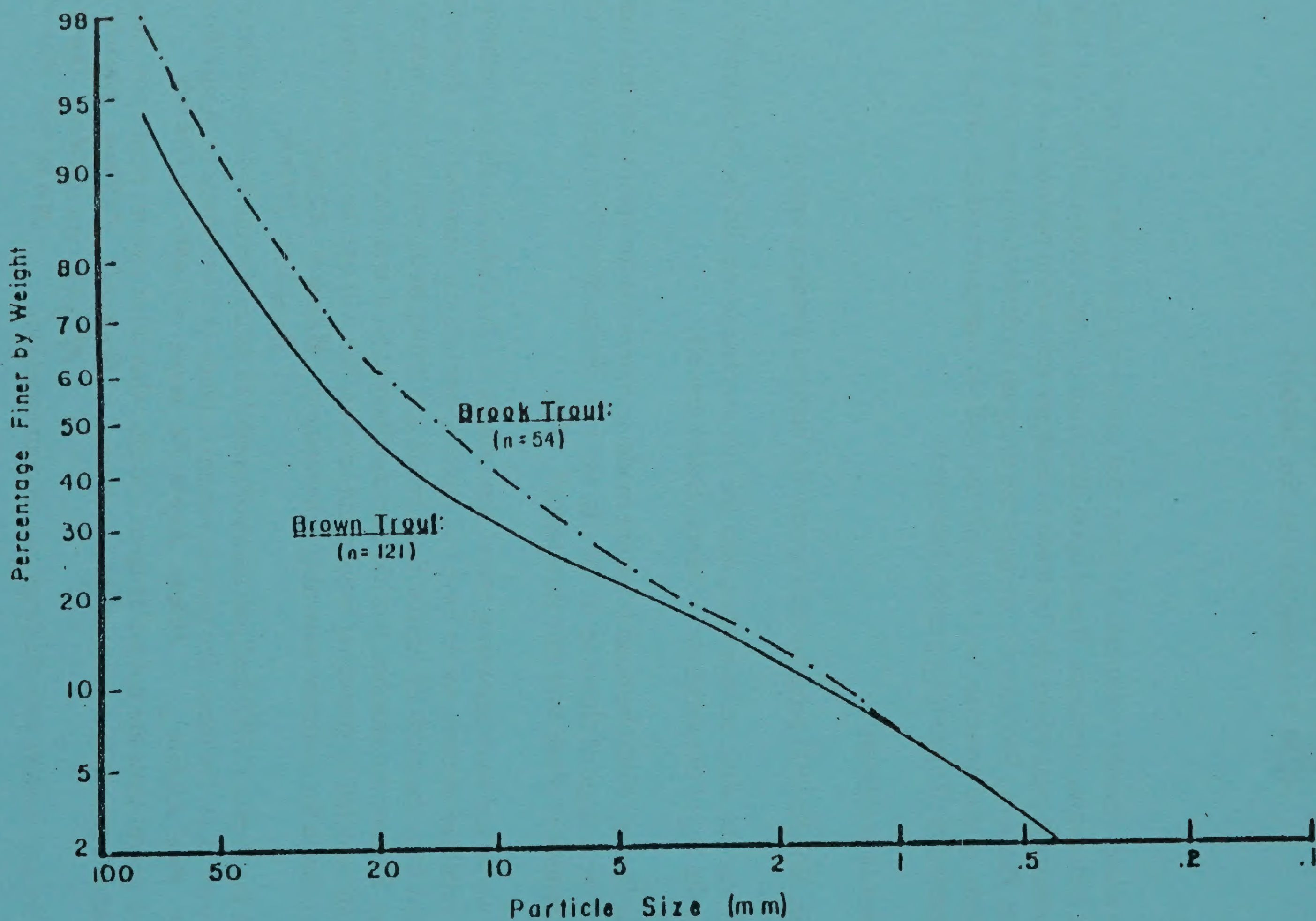
3. Run the Parker (1990) bedload transport model to determine the stability of this coarse gravel over a range of flows up to 150 cfs, our high design flow. Does this size of coarse gravel remain in place over this flow range? Yes

4. While we do not have spawning gravel size criteria for the Colorado River cutthroat trout in our small test stream, we do have bed material particle size distribution information collected from the redds of similar sized brook and brown trout from similar nearby streams. Review the attached particle size distribution plots and determine the D_{50} of bed materials selected by spawning brooks and browns. We will use these gravel sizes as our design criteria for cutthroat spawning enhancement. Brown = 22mm
Brook = 14mm

5. Re-run the Parker (1990) bedload transport model to determine the stability of the brook and brown D_{50}'s. Do these size gravels remain in place over our range of design flows?
Yes for 22mm; 14mm begin to move at over ~100cfs

6. If these gravel sizes are not stable up to 150 cfs, what other options might you consider to enhance cutthoat spawning in our test stream? Gravels >14mm should be ok!
Might consider log sills if smaller material desirable.

7. Compare and discuss your findings and recommendations.



Size distribution of bed material particles in Brown Trout and Brook Trout redds, Medicine Bow National Forest, Wyoming.

edload Computation
:\programs\wxspro20\wsc.p90
nput File: C:\PROGRAMS\WXSPRO20\WSC.OUT
un Date: 06/06/02
nalysis Procedure: c:\programs\wxspro20\wsc.p90 Parker 1990 50

D_{50} = 50 mm

Stage (ft)	#Sec	Width (ft)	Shear (psf)	Q (cfs)	Bedload (lb/s)
0.50	T	10.17	0.03	1.24	0.00
0.60	T	14.66	0.04	2.35	0.00
0.70	T	17.00	0.05	4.20	0.00
0.80	T	19.29	0.06	6.72	0.00
0.90	T	20.91	0.08	10.09	0.00
1.00	T	22.08	0.09	14.31	0.00
1.10	T	23.12	0.10	19.33	0.00
1.20	T	24.71	0.11	24.81	0.00
1.30	T	25.28	0.13	31.84	0.00
1.40	T	25.49	0.15	40.00	0.00
1.50	T	25.70	0.16	49.06	0.00
1.60	T	25.91	0.18	59.03	0.00
1.70	T	26.12	0.19	69.94	0.00
1.80	T	26.33	0.21	81.81	0.00
1.90	T	26.57	0.23	94.64	0.00
2.00	T	26.82	0.24	108.49	0.00
2.10	T	27.06	0.26	123.42	0.00
2.20	T	27.31	0.27	139.46	0.00
2.30	T	27.56	0.29	156.66	0.00
2.40	T	27.81	0.30	175.08	0.00

Stage ft	Q ft3/sec	Bedload lb/sec
0.50	1.24	0.00
0.60	2.35	0.00
0.70	4.20	0.00
0.80	6.72	0.00
0.90	10.09	0.00
1.00	14.31	0.00
1.10	19.33	0.00
1.20	24.81	0.00
1.30	31.84	0.00
1.40	40.00	0.00
1.50	49.06	0.00
1.60	59.03	0.00
1.70	69.94	0.00
1.80	81.81	0.00
1.90	94.64	0.00
2.00	108.49	0.00
2.10	123.42	0.00
2.20	139.46	0.00
2.30	156.66	0.00
2.40	175.08	0.00

Bedload Computation
c:\programs\wxspro20\wsc.p90
Input File: C:\PROGRAMS\WXSPRO20\WSC.OUT 22
Run Date: 06/06/02
Analysis Procedure: c:\programs\wxspro20\wsc.p90 Parker 1990

D_{50} = 22 mm

Stage (ft)	#Sec	Width (ft)	Shear (psf)	Q (cfs)	Bedload (lb/s)
0.50	T	10.17	0.03	1.24	0.00
0.60	T	14.66	0.04	2.35	0.00
0.70	T	17.00	0.05	4.20	0.00
0.80	T	19.29	0.06	6.72	0.00
0.90	T	20.91	0.08	10.09	0.00
1.00	T	22.08	0.09	14.31	0.00
1.10	T	23.12	0.10	19.33	0.00
1.20	T	24.71	0.11	24.81	0.00
1.30	T	25.28	0.13	31.84	0.00
1.40	T	25.49	0.15	40.00	0.00
1.50	T	25.70	0.16	49.06	0.00
1.60	T	25.91	0.18	59.03	0.00
1.70	T	26.12	0.19	69.94	0.00
1.80	T	26.33	0.21	81.81	0.00
1.90	T	26.57	0.23	94.64	0.00
2.00	T	26.82	0.24	108.49	0.00
2.10	T	27.06	0.26	123.42	0.00
2.20	T	27.31	0.27	139.46	0.00
2.30	T	27.56	0.29	156.66	0.01
2.40	T	27.81	0.30	175.08	0.02

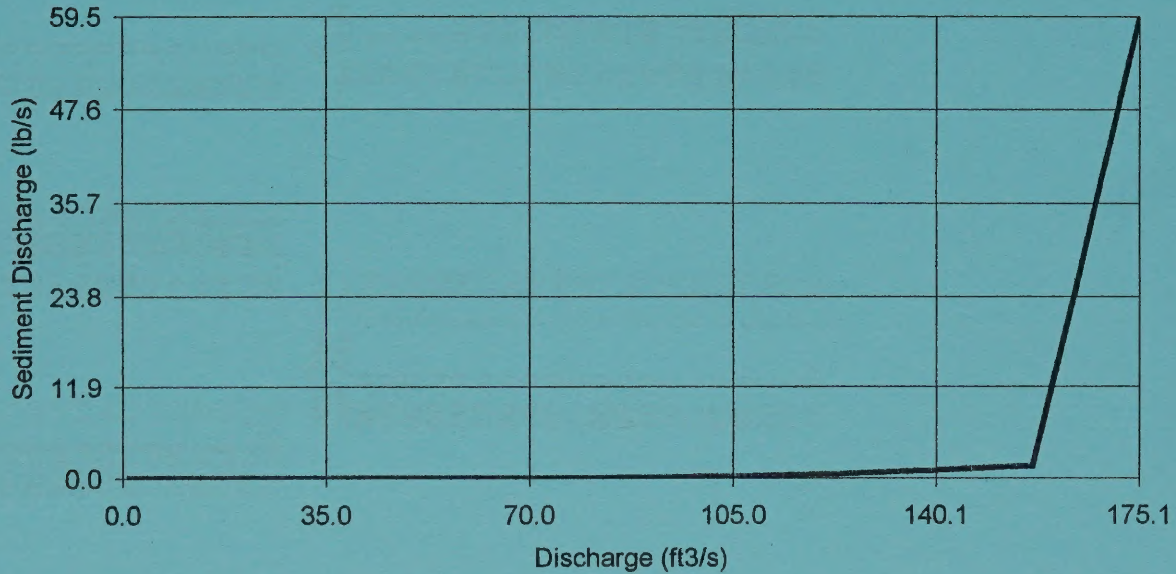
Stage ft	Q ft3/Sec	Bedload lb/Sec
0.50	1.24	0.00
0.60	2.35	0.00
0.70	4.20	0.00
0.80	6.72	0.00
0.90	10.09	0.00
1.00	14.31	0.00
1.10	19.33	0.00
1.20	24.81	0.00
1.30	31.84	0.00
1.40	40.00	0.00
1.50	49.06	0.00
1.60	59.03	0.00
1.70	69.94	0.00
1.80	81.81	0.00
1.90	94.64	0.00
2.00	108.49	0.00
2.10	123.42	0.00
2.20	139.46	0.00
2.30	156.66	0.01
2.40	175.08	0.02

Bedload Computation $D_{50} = 14mm$
c:\programs\wxspro20\wsc.p90
Input File: C:\PROGRAMS\WXSPRO20\WSC.OUT 14
Run Date: 06/06/02
Analysis Procedure: c:\programs\wxspro20\wsc.p90 Parker 1990

Stage (ft)	#Sec	Width (ft)	Shear (psf)	Q (cfs)	Bedload (lb/s)
0.50	T	10.17	0.03	1.24	0.00
0.60	T	14.66	0.04	2.35	0.00
0.70	T	17.00	0.05	4.20	0.00
0.80	T	19.29	0.06	6.72	0.00
0.90	T	20.91	0.08	10.09	0.00
1.00	T	22.08	0.09	14.31	0.00
1.10	T	23.12	0.10	19.33	0.00
1.20	T	24.71	0.11	24.81	0.00
1.30	T	25.28	0.13	31.84	0.00
1.40	T	25.49	0.15	40.00	0.00
1.50	T	25.70	0.16	49.06	0.00
1.60	T	25.91	0.18	59.03	0.00
1.70	T	26.12	0.19	69.94	0.01
1.80	T	26.33	0.21	81.81	0.04
1.90	T	26.57	0.23	94.64	0.12
2.00	T	26.82	0.24	108.49	0.28
2.10	T	27.06	0.26	123.42	0.59
2.20	T	27.31	0.27	139.46	1.05
2.30	T	27.56	0.29	156.66	1.65
2.40	T	27.81	0.30	175.08	59.51

Stage ft	Q ft3/Sec	Bedload lb/Sec
0.50	1.24	0.00
0.60	2.35	0.00
0.70	4.20	0.00
0.80	6.72	0.00
0.90	10.09	0.00
1.00	14.31	0.00
1.10	19.33	0.00
1.20	24.81	0.00
1.30	31.84	0.00
1.40	40.00	0.00
1.50	49.06	0.00
1.60	59.03	0.00
1.70	69.94	0.01
1.80	81.81	0.04
1.90	94.64	0.12
2.00	108.49	0.28
2.10	123.42	0.59
2.20	139.46	1.05
2.30	156.66	1.65
2.40	175.08	59.51

$D_{50} = 14mm$



59.5
47.6
35.7
23.8
11.9
0.0
Sediment Discharge (lb/s)
0.0
35.0
70.0
105.0
140.1
175.1
Discharge (ft3/s)

IN-CLASS PROBLEM #16 - Answer Sheet
SHM Recommendations for the Santa Fe River
BLM Training Course 7000-12

The Problem:

In Problem #13 we applied the Stream Reach Inventory and Channel Stability Evaluation system on this section of the Santa Fe River below Santa Fe, N.M. Our analysis indicated this stream was highly embedded with sand and finer gravels, aggrading, overly widened, and very unstable. Mid-channel bars were common and large bed elements such as boulders caused extensive sediment deposition and in some cases, channel blow-outs. Historic land uses coupled with extensive water diversion have contributed substantially to this current condition, and should likely be the emphasis of any watershed restoration effort.

The objective of this exercise is to explore the possible role of SHM in the restoration of the Santa Fe River. Assuming that land use practices are being modified and efforts for hydrologic restoration are underway, complete the following steps:

1. Carefully review the seven Power Point photos of the Santa Fe and your SRI/CSE scorecard from earlier today.

2. Working in pairs, develop a list of up to several SHM treatments you feel may be effective in improving habitat quality throughout this reach. If you feel there is no role whatsoever for SHM here, say so and be ready to defend your position.
   I anticipate some will respond with "no role" and others will suggest an array of possible SHM treatments. My inclination would be to recommend various types of deflectors, both single wing in a series and also double deflectors or constrictors. Such treatments would help to narrow the channel, increase water velocities, transport sand, reduce embeddedness and lead to a coarser substrate.

3. For the SHM treatments you feel may be beneficial, briefly review the cutthroat trout HSI model we worked with on Monday afternoon. Develop a list of HSI variables that may be influenced by your recommended treatments. For each affected variable, subjectively rate the degree of influence that may result from your SHM treatments. For in-class consistency, use "high", "moderate", and "low" as your ratings.
   "High" = V_4, V_5, V_7, V_8, V_9, V_{16}
   "Moderate" = V_1, V_6, V_{10}, V_{11}, V_{12}, V_{15}, V_{17}
   "Low" = V_2, V_3, V_{13}, V_{14}

4. Present your recommendations and ratings.

5. Participate in a class discussion of possible SHM treatments and your justification for the recommendations you made.

ANSWER SHEET
Pre- and Post-Course Exam
BLM Training Course No. 7000-12
Aquatic Habitat Restoration and Enhancement
Days One to Four

1. Possible correct answers include: Population status; Age, growth and condition; Reproduction strategy; Food requirements; Predator-prey relations.

2. Possible correct answers include: Spawning & incubation; larval stages/fry; juvenile; adult.

3. Pool, Riffle, Run (or glide).

4. Water and Sediment.

5. b, c, and e are correct.

6. Historical, Upstream/Downstream, and Paired Watersheds or streams are correct.

7. a, b, c, and d are correct.

8. a, c, and e are correct.

9. True.

10. Possible correct answers include: Create downstream scour pool; Promote upstream water and sediment storage; Improve passage conditions; Encourage downstream gravel bar formation; Facilitate aeration; Reduce excess water velocities; Collect and hold gravels upstream; Stabilize downcut channels; Control flow into secondary channels.

11. False.

12. True.

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Day 5

Monitoring and Reporting on Aquatic Restoration Efforts
Brett Roper   Friday 0800:1200

1. Why monitoring projects fail.
    a. Procedural Failure
    b. Design Failure
2. Design Failure – often referred to as statistics problems
    a. Methods can't measure.
    b. Study to short.
    c. Inadequate problem analysis.
    d. Misunderstanding of system.
    e. Weak statistical design.
3. Statistical relationships to design failures
    a. Type I errors
    b. Type II errors
4. Statistical solutions to design failures
    a. Understanding variation.
        i. Choice of variables
        ii. Permanent vs. temporary sites.
    b. Statistical design to detect differences
        i. Sample size
            1. Variance
            2. Error Rates
            3. Detectable effect size
        ii. Stratification
5. Open discussion to discuss participants concerns with monitoring.

Closeout &
Evaluation

Post-course Exercise
BLM Training Course No. 7000-12
Aquatic Habitat Restoration and Enhancement

GS Grade_________ **% of time using materials learned in this class ______**

Note: For multiple choice, more than one answer may be correct!

1. Three types of fish life history information that may be useful in the planning and design of aquatic habitat restoration projects include________________, ________________, and ________________________.

2. Three life stages of your target fish species to be considered in the planning and design of aquatic habitat restoration projects include__________________,__________________, and __________________.

3. The three basic "mesohabitat" types are__________________,__________________, and ___________________.

4. Lane's Balance can be useful in qualitatively describing the distribution of____________ and ________________throughout a watershed.

5. Macrohabitat characteristics that are commonly used to segment rivers into reaches may include:
(a) nose velocity
(b) water quality
(c) channel morphology
(d) percent glides
(e) hydrology
(f) all of the above
(g) none of the above.

6. The three general types of reference stream approaches include ___________________, __________________________, and __________________________________.

7. The determination of instream flow requirements for a river reach may involve the use of computer models such as:
(a) IHA
(b) PHABSIM
(c) WinXSPRO
(d) RHABSIM
(e) DENIL
(f) all of the above
(g) none of the above.

8. When analyzing a potential fish passage barrier, we are typically concerned with:
(a) barrier geometry
(b) macroinvertebrate density
(c) barrier hydraulics
(d) sodium adsorption ratio
(e) fish swimming and leaping capabilities
(f) larval drift
(g) all of the above
(h) none of the above.

9. Fish passage barriers can be both natural and man-made. True or False

10. Four habitat benefits that may result from a properly designed and constructed log overpour include ______________________________, ____________________________, ______________________________, and ______________________________.

11. Properly classifying the stream channel assures success of a restoration project. T or F

12. Hydraulic uncertainty is always a concern with structural habitat management. T or F

Misc.